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Decision Modeling for Smart Climatology

by

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30 November, 2008

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13. ABSTRACT (maximum 200 words)

The purpose of smart climatology is to provide information that would be useful in operational planning at lead times of two to four weeks or greater. Decisions made at shorter lead-times are generally informed by forecasts. One of the challenges in designing a new climatology data system—to include generation, storage, and access—is anticipating how the data might be used, and therefore how to design the system to provide the most useful data in their most useful format. This report uses an operations research / decision analysis (OR/DA) approach to prototype the process of using smart climatology data in planning, and identify challenges and key features of decision-relevant climatology data system.

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Decision Modeling for Smart Climatology

The purpose of smart climatology is to provide information that would be useful in operational planning at lead times of two to four weeks or greater. Decisions made at shorter lead-times are generally informed by forecasts. One of the challenges in designing a new climatology data system—to include generation, storage, and access—is anticipating how the data might be used, and therefore how to design the system to provide the most useful data in their most useful format. This report uses an operations research / decision analysis (OR/DA) approach to prototype the process of using smart climatology data in planning, and identify challenges and key features of decision-relevant climatology data system.

1 How does METOC information create value?

While some commercial forecast and climatology providers, such as The Weather Channel, profit from the entertainment value of forecasts, military meteorology and oceanography (METOC) products create value by influencing operational consequences.[1] Taking this perspective, an OR/DA framework can be used to analyze and improve:

1) how METOC information is used in decision-making (mission planning and execution);
2) the design of METOC products for communication to operational decision-makers; and
3) the operational value created by METOC information.

The OR/DA framework makes some basic assumptions that may be non-intuitive to the METOC community.

First, **information can only improve operational consequences if it affects decisions** – in other words, if the information induces an operational end-user (hereafter, commander) to alter her course of action from what it would have been without information (or with different information) and that alteration leads to better consequences.

There is no qualitative difference between METOC forecasts and climatology. Both are information sets and can be interpreted as conditioning the probability distribution of future METOC events. Therefore, the treatment of forecasts and climatology is analogous in OR/DA analysis.

In OR/DA analysis, **all forecasts are treated as probabilistic**. Even if a deterministic forecast is offered – e.g. “conditions will be green for the mission” or “winds will be 20 knots from the south, with low turbulence” – the commander knows that this is not guaranteed, and may hedge his decisions based on his confidence in the forecast(er) or based on his experience with the predictability of the situation. Climatology data therefore conditions[2] the probability distribution of future METOC conditions, affecting the assessed (objectively or subjectively measured) likelihood of future METOC conditions.

Operational consequences are produced by the interaction of commanders’ decisions with METOC events. METOC conditions alone do not determine the mission consequences. If they did, then it would not be valuable for commanders to have METOC information – the same consequences would occur if commanders simply waited for the mission and METOC events to unfold, without accessing or using METOC products.

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[1] Commercial forecast and climatology providers do not provide only entertainment value – they also produce products and services that create value by influencing decisions.

[2] The word “condition” is used here as a verb, defined as “to subject to something as a condition; to make dependent on a condition to be fulfilled; to make conditional *on*, *upon*” (from Oxford English Dictionary online, http://dictionary.oed.com/entrance.dtl), used in probability to indicate the probability of an event given (conditioned on) the occurrence of another event.

Therefore, **OR/DA analyses are meaningful within a given decision context**, or scenario. The best policies for using METOC information (decision policies), the best design of a METOC product, and the value of METOC information are all dependent on the specifics of a given decision context – or mission scenario. Policies, product design, and value-of-information cannot be analyzed without a model of how METOC information is used.

Decision policies, product design, and information value are best analyzed in expectation. The consequences of an actual mission, with a particular forecast and verification should not be used in isolation to assess the value of a METOC product or to plan for future uses of the product. To use a single event in analyzing a METOC product would be like saying that someone is a good gambler because he won $1M on the slot machine his first day in Las Vegas. The OR/DA approach analyzes METOC information and decisions *ex ante*, i.e. before the prevailing conditions at the time of verification become known.

1.1 OR/DA Modeling

In order to use an OR/DA approach to using, designing, and valuing METOC products, the following elements, and the relationships among them must all be understood, and if possible modeled, for a particular decision context:

- METOC information – including both forecasts and climatology, if applicable;
- decisions made using METOC information;
- METOC outcomes (events), i.e. conditions that actually prevail in forecast verification; and
- mission consequences.[3]

A few of the elements and relationships pose particular challenges for the analyst, such as the statistical relationship(s) among climatology, forecasts, and METOC outcomes. The term "outcome" is used hereafter to refer to the METOC events and conditions that actually prevail, but cannot be perfectly predicted in advance. Modeling how decisions interact with METOC conditions to produce mission consequences is often one of the most challenging parts of the problem, for a number of reasons discussed in more detail in Section 7, and requires expertise from multiple disciplines, including details related to a mission-specific decision context.

In the Smart Climatology project, this was the major hurdle to OR/DA modeling. In order to build a useful model, it is necessary to be able to communicate with an operational subject-matter expert or end-user who can assess, at least qualitatively, what are the commander's available courses, what are the METOC conditions that would affect mission consequences, and the mission consequences that would be produced by each combination of course of action and METOC outcome. For example, in modeling a missile exchange, the subject-matter expert would need to be able to indicate at a minimum the effective range of each available missile type under various METOC conditions, and the number of strikes each aircraft and vessel can sustain before being incapacitated. In this project, a Naval War College teaching scenario was used as the decision context, and therefore the area experts were not actually operators who could provide assessments of the necessary parameters. Moreover, for reasons further described in Section 2, performance data for platforms and weapons systems under different METOC conditions are not necessarily available through other routes.

1.2 Measuring Value of Forecasts

Value-of-information (VOI) is a OR/DA concept that is central to this report, and that has been used in the meteorology literature to frame problems about the best use of climate and forecast information, and

[3] To indicate measurable operational outcomes or mission results, this report uses the term consequences to refer to all relevant results/benefits/costs associated with the conduct and outcome of an operation.

to generate estimates of the socioeconomic value of forecasts. VOI measures the value of information, such as a forecast or climatological information, in a particular decision context. Although the value may be measured in units of dollars, mission-specific value may also be measured in units specific to the decision context. VOI is a specific measure of type 3 goodness of a forecast, by Murphy (1993)'s definitions.

VOI is measured as the expected difference in consequences under two information scenarios: a baseline (less informative) scenario, and an improved (more informative) scenario. For example, the baseline scenario could use maximum daily temperature, while the more-informative scenario includes predicted hourly temperature. A baseline scenario could be a categorical precipitation forecast, while the more-informative scenario is a probabilistic precipitation forecast. An example we will explore more is a baseline where a single forecast is provided for a valid period, and the more-informative scenario includes climatology followed by a forecast for the same valid period.

Since consequences are affected by decisions (in turn affected by METOC information), and by METOC outcomes, each of the elements and the relationships among them must be modeled. This implies that efforts to integrate METOC forecasts in decision-making should focus around a particular decision, rather than around a particular METOC phenomenon or model.

VOI for METOC products may be used as a justification for METOC budgets, as they provide a quantitative estimate of the benefits of METOC information. The primary reasons the VOI framework is used here are:

- VOI highlights the relationships between the generation of METOC information, the way it is used, and the most valuable characteristics of that information.
- VOI analysis includes identifying optimal decision rules as a function of METOC information – and therefore can help identify improvements in the use of information.
- VOI provides a mission-centric means to measure information quality that can be used as a yardstick for evaluating improvements to the information-generation system, such as a forecasting process or a climatology database.

The OR/DA approach to measuring value contrasts with methods that attempt to measure individuals' willingness to pay for METOC forecasts. These methods include survey-based approaches such as contingent valuation and methods to tease out revealed preferences, by observing behavior including market prices.[4]

1.3 Special challenges for climatology

OR/DA analyses using climatology information pose special challenges. Decisions that may be influenced by climatology require long lead times, of at least two to four weeks but potentially one to two years or more – otherwise, the more precise information provided by METOC forecasts would be used. Although training and planning occur with much longer lead times, most operational decisions are not made – or are not made irrevocably – until lead times of a few hours to a few days.

In addition, decisions based on climatology are rarely the last decisions that affect METOC-dependent mission consequences. In general, for any specific mission scenario, there is some flexibility at shorter lead times to adjust the mission and influence METOC-dependent mission consequences. Therefore, the analysis of the use of forecast information must be included in the analysis of the use of climatology information.

Nevertheless, climatology provides value by informing the long-lead-time decisions that create constraints for the later decisions. For example, if we do not plan, at a long lead-time, to have a particular

[4] Johnson and Holt (1997) give an accessible description of other approaches to measuring forecast value.

asset available in-theater, then in mission execution, alternative courses of action are limited by the non-availability of that asset. Some US Navy bases, for example, set conditions of readiness (TCCOR) on the basis of climatology – Kadena is in TCCOR 4 throughout during the typhoon season, identified based on climatology. When the base is in TCCOR 4, they make preliminary preparations to facilitate preparations required once a storm is forecast.

A naval scenario is used here to illustrate the use of forecast and climatology information in decision-making, and to illustrate the analysis and measurement of their value in improving expected mission consequences. The long-lead-time decision that is based on climatology data is where to station Blue (U.S.) bombers, that may later be called upon (with a short lead-time) to lay sea-mines to defend a Green (neutral) beach against a Red (enemy) amphibious attack.

2 Modeling an operational scenario using OR/DA approach

An OR/DA approach to using, modeling, and evaluating METOC information – whether forecasts or climatology – focuses on two elements that are usually outside the scope of METOC analyses, but must be brought into Tier III of Battlespace on Demand:[5]

1. decisions; and
2. consequences.

The interacting systems through which METOC information creates value in a one-time (tactical) decision context are depicted in Figure 1a. As discussed earlier, METOC conditions (the outcome) combine with decisions and subsequent actions to determine mission consequences. Decisions are informed by METOC information – in Figure 1a, this is depicted as the forecast. The forecast is related to the METOC outcome – ideally, it would predict the outcome perfectly. In reality, both the forecast and the outcome are related to the evolution of the atmosphere and oceans. As indicated in Figure 1a, the forecaster receives information inputs – including observations and model output – that are affected by the past and current state of the atmosphere and oceans. The METOC outcome is also affected by past and current state of the atmosphere and oceans. Figure 1b depicts the way these relationships are simplified for modeling in OR/DA. Not all elements are modeled; instead, the relationship between the forecast and METOC outcome is modeled statistically.

Some basic notation introduced below and summarized in Table 1 will help clarify this discussion.

For now, the term "forecast" will be used to refer to any METOC message – which, in an OR/DA framework, could be either a forecast or climatology. If the forecast is accurate or skillful, the METOC outcome, w, will be non-independent of the forecast φ. In Figure 1a, this relationship is depicted such that the physical systems that determine METOC outcomes also influence the information available to the forecaster and thereby the forecast.

In OR/DA modeling, the physical systems (atmosphere, oceans) are not modeled directly. Rather, the dependence of both the METOC outcome and the forecast on the physical systems are modeled by a joint probability distribution over METOC outcomes and forecasts, as depicted in Figure 1b.

Sections 2.1 through 2.4 below describe the modeling of the elements and relationships depicted in Figure 1a. Sections 2.5 and 2.6 describe the analysis of the model, including calculation of the value of METOC information. Section 3 illustrates this modeling and analysis process using a decision context derived from a Naval War College teaching scenario to illustrate the modeling process.

[5] The three tiers are described in Battlespace on Demand, Naval Oceanography Program Commander's Intent, released November 2006.

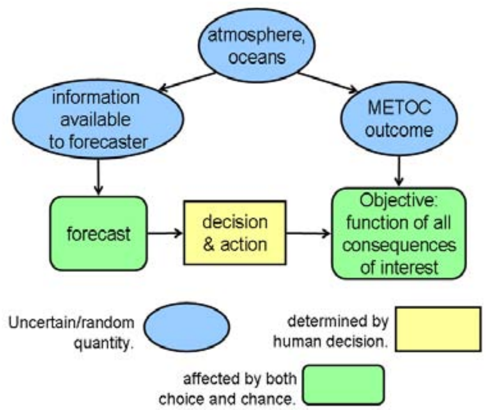

Figure 1a: Interacting systems that produce forecast value.

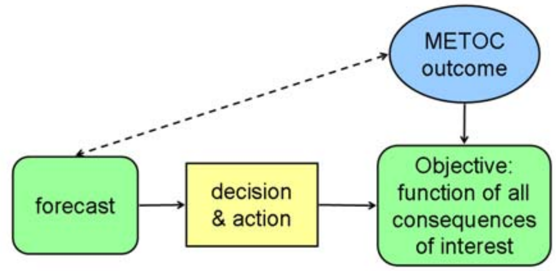

Figure 1b: Modeled systems that produce forecast value.

2.1 Alternative Courses of Action

The first two steps are to model the available courses of action (hereafter, alternatives) and the METOC conditions that will, in combination, affect operational consequences. The decision is a choice of exactly one alternative (a) from a set of available alternatives (A). In any operation there are many decisions that are made, and as in any modeling effort, modeling the available alternatives involves a simplification of the real-world situation. One of the major simplifications is that decisions that do not interact with METOC conditions in determining consequences may be neglected.

Table 1: Notation for single-stage decision modeling

A	the set of all alternatives (courses of action) available in a given decision context
a	a single alternative, $a \in A$ (may be multi-dimensional)
W	the set of all possible METOC outcomes, relevant to a given decision context
w	a single METOC outcome that may prevail, $w \in W$ (may be multi-dimensional)
Φ	the set of all forecasts that are possible, *ex ante* (i.e. before the forecaster has evaluated available data, and generated a forecast) in a given decision context
φ	a single METOC forecast, $\varphi \in \Phi$ (may be multi-dimensional) In a simple, one-state decision (as described in Section 2), φ is a state of information.
$v(a,w)$	a scalar measure of the consequences of the selection (and implementation) of alternative a and the occurrence of METOC outcome w; for simplicity, we will assume that lower values of v are preferred – i.e. v is measured as costs, or negative consequences
$\alpha(\varphi)$	a decision rule that describes the alternative the commander will select if forecast φ is issued; defined $\forall \varphi \in \Phi$
$\alpha^*(\varphi)$	the normative (optimal) decision rule; $\forall \varphi \in \Phi$, $\alpha^*(\varphi) = \min_{a \in A} E_{w\|\varphi}\left[v(a,w)\right]$. The notation $E_{w\|\varphi}[\ ]$ means the expectation taken with respect to the random variable w, conditioned on the forecast φ.
Φ_R	the set of all possible reference forecasts; if the reference forecast is simply climatology, $\Phi_R = \Phi_C = \varphi_C$, i.e. there is only one possible forecast
φ_R	a single reference forecast, $\varphi_R \in \Phi_R$ (may be multi-dimensional)

2.2 METOC Outcomes

METOC outcomes that affect consequences of concern must be modeled, as must the functional relationship between METOC outcomes and consequences (discussed in Section 2.3).

METOC outcomes **that affect consequences** must be modeled in sufficient detail that:

1. the probability distribution function – joint over **all relevant variables** – can be modeled, for each possible state of information;[6] and
2. consequences as a function of each decision-METOC outcome combination can be modeled.

Relevant METOC variables are those that will significantly affect consequences and/or decisions. Identifying the set of relevant METOC variables is a modeling challenge, and should be done in conjunction with modeling consequences and decisions (see Sections 2.1 and 2.3).

[6] A "state of information" is one of the possible forecasts or climatology data draws, or a single realization of a forecast or data draw. If there are multiple states – either decision opportunities or forecast opportunities – the state of information will describe the realizations of all information and decision opportunities preceding a given point.

2.3 *Consequences*

To indicate measurable operational outcomes or mission results, this report uses the term consequences to refer to all relevant results/benefits/costs associated with the conduct and outcome of an operation.

When METOC conditions are operationally relevant, they determine consequences in combination with decisions, as represented in Figure 2. For example, the damage caused to an air base by a typhoon is determined by both METOC outcomes – i.e. how severe the typhoon conditions are at the base – and decisions – i.e. what protective actions such as evacuation of aircraft or personnel, protecting buildings and other equipment were taken before the storm arrived.

Therefore, modeling requires measures of consequences that commanders care about, as a function of each decision-METOC outcome combination. Examples of mission-specific consequences include lives lost, targets destroyed, troops (or vehicles) landing successfully. Consequences may also be measured in terms of risk, as in probability that Red combat power exceeds Blue combat power or probability that the mission objective is achieved.

To be complete, consequences should include METOC impacts plus direct consequences of decisions – e.g. protection costs, relocation costs for bombers.

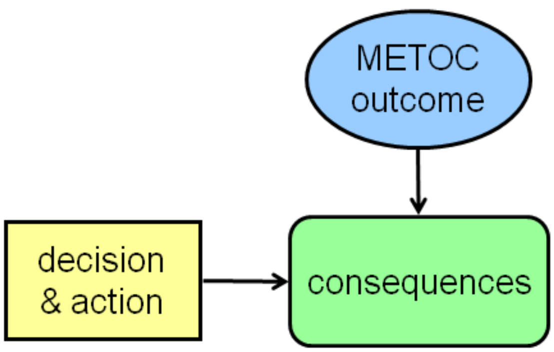

Figure 2a: METOC outcomes interact with decisions to produce consequences.

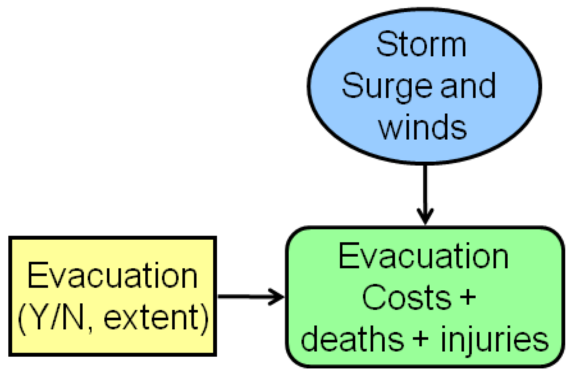

Figure 2b: Example of interaction for tropical cyclone evacuation decision.

Modeling decisions (assumptions) must be made, to generate the function $v(a,w)$, defined in Table 1. If both alternatives A and METOC outcomes W are discrete, the function $v(a,w)$ can be represented with a decision matrix in which the alternatives form the rows, and the METOC outcomes form the columns, and the cells gives the consequences of each decision-outcome pair.

Table 2: Decision matrix example.

		w	
		1	2
a	1	$v(1,1)$	$v(1,2)$
	2	$v(2,1)$	$v(2,2)$

2.4 *METOC Information*

METOC information – whether forecasts or climatology – must also be modeled, as well as the relationship between information and outcomes. Information's role is to determine probabilities of possible METOC outcomes. In other words, the relationship between information (whether forecast or climatology) and outcomes must be modeled probabilistically.

A probability distribution – joint over **all relevant variables** – must be modeled, conditional on each state of information (possible realization of the forecast, φ). Some notation given in Table 1 will help make this discussion more precise.

The relationship between w and φ is described by a joint probability density function (if w and φ are continuously valued) or a joint probability mass function (if w and φ take on only discrete values). For simplicity, both pdfs and pmfs are referred to as probability distributions.

- **Marginals:** The notation $P[w]$ or $P[w=i]$ indicates the non-conditioned (also called overall, marginal, or climatological) probability of a given METOC outcome occurring. The notation $P[\varphi]$ or $P[\varphi=j]$ indicates the marginal probability of a given forecast being issued.

  Forecasters generally do not think of a forecast as a random variable – a forecast is generated either objectively or by application of forecaster's knowledge. However, the forecast realization can be thought of as random before observations and model runs that determine the forecast (or condition the generation of a climatology) are generated. At this point, many different forecasts are possible, and some are more likely than others. This effect is modeled by the probabilistic treatment of the issuance of forecasts.

- **Conditionals**: The notation $P[w|\varphi]$ or $P[w=i|\varphi=j]$ indicates the probability of a given METOC outcome ($w=i$) occurring given that a particular forecast ($\varphi=j$) has been issued (conditioned on a particular forecast).[7]

- **Joint probabilities**: The notation $P[w,\varphi]$ or $P[w=i,\varphi=j]$ indicates the probability that two events will both occur: a given forecast will be issued ($\varphi=j$) and a given METOC outcome will occur ($w=i$). This means that $P[w,\varphi]\leq P[w|\varphi]$, and specifically $P[w|\varphi]=\dfrac{P[w,\varphi]}{P[\varphi]}$. This is Bayes Rule (Clemen, 1997).

Quantifying the statistical relationship between METOC information and METOC outcomes may be difficult. In general, measures of forecast accuracy and skill may be used to model these relationships. When more than one METOC information set is involved – as when both climatological information and a forecast may be used at different stages in planning for a single mission – the relationships between climatology and the forecasts, and among multiple forecasts, if applicable, must also be modeled, as well as their statistical relationship to METOC outcomes. Multiple information sets are addressed in Section 4.

[7] We can also write $P[\varphi|w]$, the probability that forecast φ was issued, given that METOC outcome w has occurred. This kind of conditional is less common, because commanders learn the forecast chronologically before the METOC outcomes occur.

2.5 Decision Policies

How information will affect decisions (and thereby actions) must be modeled, i.e. the decision to be taken must be modeled as a function with a domain of every possible state of information. In the notation in Table 1, the possible states of information are denoted by Φ, and a single possible state of information is φ. A decision policy $\alpha(\varphi)$ is a function that indicates, for each φ, which action a will be selected.

A decision model falls into one of two major categories: normative or descriptive. In a normative model, the assumption is that the decision maker optimizes, by minimizing expected total cost.[8] In a descriptive model, the decision maker's behavior may not be optimal, and the model seeks to replicate his actual behavior under each state of information. Descriptive modeling is therefore much more difficult; to develop a good descriptive model, we would need to interview commanders and/or observe their behavior to try to understand not only what they have done in the past, but what they would do under hypothetical situations – because we must know $\alpha(\varphi)\ \ \forall\varphi\in\Phi$.

We focus on normative modeling in part for simplicity, but also because we hope to induce people to behave optimally (normatively), and because in many cases, forecasters are implicitly called upon to make mission-related decisions – by issuing a particular forecast, they may effectively force commanders into a particular course of action. Therefore, the forecaster should understand what makes a decision optimal in the decision context he supports.

The role of OR/DA analysts is to model decision situations, and then to optimize decisions, often under conditions of uncertainty. To optimize, an OR/DA analyst would try to solve the following problem, for all values of φ:

$$a^* = \min_{a\in A} E_{w|\varphi}\left[v(a,w)\right] \tag{1}$$

The solutions to Eq. (1) become the decision rule, as indicated in the definition of $\alpha^*(\varphi)$ in Table 1.

This problem may be difficult or easy to solve, depending on the joint probability distribution of w and φ, on the constraints on a, and on the form of the function $v(a,w)$. For discrete w,

$\alpha^*(\varphi) = \min_{a\in A} E_{w|\varphi}\left[v(a,w)\right] = \min_{a\in A} \sum_{w\in W} v(a,w)\times P\left[w\,|\,\varphi\right]$.

2.6 Value of Information

The VOI is the expected difference in consequences under two information systems: a baseline (less informative) system, and an improved (more informative) system. In order to estimate the value of information provided by the more informative system – for example, the value of a METOC forecast – we must model a baseline or reference system, which we will call a reference forecast.

The reference forecast could be a forecast that is less accurate, or it could be the lack of a forecast – in which case, climatological frequencies are generally used as the reference forecast. If the reference forecast is simply climatology, $\Phi_R = \Phi_C = \varphi_R$, i.e. only one forecast is possible. In that case, φ_R is a probability distribution across all METOC outcomes, and specifically $\forall w$, $P\left[w\,|\,\varphi_R\right]$ = the climatological probability (long-run frequency) of METOC outcome w.

The modeled alternatives, METOC outcomes, and consequences do not change when a reference forecast is introduced. The decision policy, however, must be re-assessed for the possible values of the reference

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[8] Equivalently, optimization can be maximizing expected net benefit (costs and benefits can be combined by treating costs as negative benefits and vice versa).

forecast. The identification of the decision policy proceeds exactly as described in Section 2.5, substituting φ_R for φ. In other words, find $\alpha_R(\varphi_R)$, $\forall \varphi_R \in \Phi_R$. When the reference forecast is climatology, there is only one possible state of information, therefore, $a = \alpha_R(\varphi_R)$ is a constant. Using a normative decision policy for the reference forecast,

$$\alpha^*_R(\varphi_R) = \min_{a \in A} E_{w|\varphi_R}\left[v(a,w)\right].$$

Once the decision policy is identified, the expected consequences given the reference forecast is $E_{w|\varphi_R}\left[v\left(\alpha^*_R(\varphi_R), w\right)\right]$.

The VOI is defined as follows:[9]

$$E_{\varphi_R}\left[E_{w|\varphi_R}\left[v\left(\alpha^*_R(\varphi_R), w\right)\right]\right] - E_{\varphi}\left[E_{w|\varphi}\left[v\left(\alpha^*(\varphi), w\right)\right]\right] \tag{2}$$

3 Modeling the single-stage Halsey scenario

A model of force-on-force interactions has been developed to illustrate how METOC information could be used in operational planning and how it would influence execution of operations.

The model describes a scenario in the near future in which a near-peer competitor (Red) launches an amphibious invasion on a neutral (Green) beach in East Asia. Blue (U.S. Navy) defends, while Green does not participate.

The model includes operational decisions by both Blue and Red that are made on the basis of their respective objectives as well as climatology and a near-term (72 hours and less) METOC forecast.

Red launches an unanticipated amphibious attack. Red's effective forces include both amphibious vessels and escorts. Blue has an aircraft carrier in the region, and it is assumed that Blue fighters have swept the skies, incapacitating any Red air power. Moreover, because the attack is launched with no warning, Red submarines are not patrolling close enough to the battle to reach the area in time to be involved.

The engagement therefore consists of a missile exchange between Red's sea forces and Blue's air forces. The consequences of missile exchange are modeled using a simple salvo model following Hughes (1995). Later (Section 5), the possibility of Blue dropping sea-mines to protect the beach will be added.

3.1 Alternative Courses of Action

In the single-stage Halsey scenario, the Blue decision is a choice between two missile types for an air attack on Red vessels. The missiles differ in their guidance system – Type A is METOC-sensitive, and can only be used effectively in certain METOC conditions. Each fighter can carry more Type A than Type B missiles in a single sortie. Therefore, Type A would be preferred when METOC conditions allow its use. Type B uses an all-weather GPS guidance system, which may be used regardless of METOC conditions. For the Halsey scenario, Blue's alternatives are:

$$a \in A = \{\mathrm{A}, \mathrm{B}\}$$

where a =A if Type A missiles are used, and a =B indicates that missile of Type B is selected.

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[9] This formula applies when $v(a,w)$ is in units of cost or negative consequences (to be minimized). If $v(a,w)$ is in units of benefit (to be maximized), then VOI = $E_{\varphi}\left[E_{w|\varphi}\left[v\left(\alpha^*(\varphi), w\right)\right]\right] - E_{\varphi_R}\left[E_{w|\varphi_R}\left[v\left(\alpha^*_R(\varphi_R), w\right)\right]\right]$.

In the Halsey scenario, Red also has a decision to make – Red escort vessels have two types of anti-air missiles, C and D. Red's Type C missiles are weather-sensitive, and in each salvo the escorts can fire more rounds of Type C missiles than Type D missiles, which may be used in more METOC conditions.

3.2 METOC Outcomes

In the Halsey scenario, the relevant METOC outcomes are those that affect the ability of Red and Blue to use different types of missile guidance systems – for example, less expensive (e.g. radar guided) or longer-range missiles would be more sensitive to atmospheric conditions and sea state than more expensive (e.g. GPS-guided) or shorter-range missiles.

For simplicity, we will model METOC outcomes as they affect the usability of each type of missile, both Blue and Red. In other words, $W=\{1,2,3,4\}$ where $w=1$ indicates that all missile guidance systems can be used, $w=4$ indicates that only all-METOC GPS guidance systems can be used, and $w=2$ or 3 indicates that some systems can be used and others cannot. Table 3 indicates the effectiveness of the four (two Red and two Blue) missile types.

Outcomes may be defined by multiple METOC parameters – for example, ceiling and visibility. We are therefore making the assumption that, as long as a guidance system can be used, its effectiveness is neither reduced nor enhanced by METOC conditions. If it is possible to estimate the probability distribution over these definitions of METOC outcomes, and there are no further operational impacts caused by METOC conditions, then METOC outcomes are modeled in sufficient detail.

Table 3: Relationship between METOC outcomes and missile use.

Can missile be used in these METOC conditions? (Y/N)

		METOC outcome (w)			
Missile Type		1	2	3	4
Blue	A	Y	Y	N	N
	B	Y	Y	Y	Y
Red	C	Y	N	N	N
	D	Y	Y	Y	N

3.3 Consequences

In the missile-selection problem, the consequences of concern include the results of the missile battle – the number of Red and Blue assets destroyed (or surviving) as well as the direct cost of decisions – the expenditure of missiles. Using more costly missiles implies more severe consequences than using less costly missiles.

For modeling purposes, we will assume that the costs of missiles are negligible in comparison with the results of the engagement. The two overriding consequences of the engagement are the destruction of Red vessels and Blue aircraft. If we further assume that the defense of the island against Red's amphibious attack is so important that the loss of Blue aircraft can be neglected, and the commanders will focus only on the destruction of Red landing capability, then we can define consequences as the number of Red landing vessels surviving the missile attack. To make the consequence measure applicable to an expanded scenario that includes climatology (treated in Section 5.3), we will actually define

$$v(a,w) = \text{number of Red landing vessels surviving to land.}$$

Because Red will be able to directly observe METOC conditions before choosing missiles, Red will use Type C missiles whenever that will lead to their best result, and otherwise will use Type D missiles.

Therefore, in Sections 2 and 3 we will suppress notation for this choice. In Appendix A, Blue's missile choice is denoted a_2 and Red's missile choice is denoted a_3.

Clearly, Blue commanders will want to choose $a \in A$ to minimize $v(a,w)$. However, neither Blue nor Red can control w. The task at hand is to model the function $v(a,w)$, which can then be represented in a decision matrix, with two rows – for alternatives A ={A,B} – and four columns – for METOC outcomes W ={1,2,3,4}.

The modeling of $v(a,w)$ requires several assumptions and is based on the basic salvo model by Hughes (1995), pitting Blue aircraft against Red vessels. A few of the most important assumptions include:

- Missiles are either usable or unusable, according to METOC conditions, as detailed in Table 3. If missiles are usable, all fired missiles are effective.
- Red has two vessel types – escorts and landing craft – and Blue does not distinguish between them in targeting. Parameters such as number of missiles fired per salvo per vessel are weighted averages based on the fraction of escort vessels among total Red vessels, and assuming no armament on the landing vessels.
- Fixed number of missiles fired per salvo (which corresponds to a fighter sortie) per aircraft/vessel until aircraft/vessel is disabled; thereafter, it neither fires nor is fired upon.
- Each aircraft/vessel can sustain a given number of missile strikes before becoming disabled; in each salvo, each aircraft/vessel can defend effectively against a fixed number of incoming missiles.

The assumptions are detailed in Appendix A, including the starting number of aircraft and vessels of each type, the number of missiles of each type that can be fired per salvo, the staying power and defensive capability of each platform.

Table 4 shows the consequences of each alternative-METOC outcome pair. Small values are desirable for Blue, because they indicate a smaller Red force making landing. The consequences range from zero Red landing craft surviving,[10] to 200 landing craft surviving, which is 100% of the Red fleet.

Table 4: Decision matrix: Number of Red landing craft remaining after missile battle.

$v(a,w)$		w = 1	2	3	4
a	A	118	0	200	200
	B	151	75	75	75

3.4 METOC Outcomes and Information

Any information that will be received before Blue commits to a relevant decision must be modeled. In this case, the decision is the choice of a missile type. There is a delay while missiles must be assembled and loaded and the fighters travel from the aircraft carrier to the engagement zone. In addition, observations of the engagement zone, from a distance, will be imperfect. Therefore, this decision must be made on the basis of a forecast of METOC conditions in the engagement zone.

We will assume that the missile-selection decision (described in more detail in Section 3.5) will be made on the basis of a 12-hour forecast. We will further assume that the forecast is a categorical forecast of the

[10] Note that the METOC outcome determines the missile type that Red may use, therefore in METOC conditions w =2, Red will have to use its Type B (less effective) missiles. When they go up against Blue's Type A missiles, the entire Red fleet is destroyed.

METOC outcomes defined in Table 4 above, and describes the performance of both Red and Blue missiles. In other words, the forecast $\varphi=1$ indicates that conditions corresponding to $w=1$ (all missile guidance systems are usable) are anticipated. Because the forecast is imperfect, the issuance of the forecast $\varphi=1$ does not necessarily imply that $w=1$ will occur. Instead, the relationship is described by a joint probability distribution ($P[w,\varphi]$), given in Table 5, or by conditional ($P[w|\varphi]$) and marginal ($P[\varphi]$) distributions that can be derived from the joint distribution. The values given below are illustrative only; in a real problem, they would be modeled based on historical observations and forecast accuracy measures.

Table 5: Conditional, joint, and marginal probability distributions of forecasts and METOC outcomes.

	$P[w,\varphi]$	w = 1	2	3	4
φ	1	0.32	0.07	0.05	0.02
	2	0.03	0.14	0.02	0.01
	3	0.01	0.02	0.12	0.03
	4	0.01	0.02	0.03	0.12

	$P[w\|\varphi]$	w = 1	2	3	4	$P[\varphi]$
φ	1	0.70	0.15	0.10	0.05	0.45
	2	0.15	0.70	0.10	0.05	0.20
	3	0.05	0.10	0.70	0.15	0.18
	4	0.05	0.10	0.15	0.70	0.18

3.5 Decision Policies

In the Halsey scenario, we will model decisions normatively. Therefore, we want to choose, for each $\varphi\in\Phi$, the action $a\in A$ that minimizes the expected number of Red landing vessels surviving the missile battle. We calculate, $\forall\varphi\in\Phi$, $\forall a\in A$

$$E_{w|\varphi}\left[v(a,w)\right]=\sum_{w\in W}v(a,w)\times P[w|\varphi].$$

Next, following Eq. (1),for each φ, we identify the action a that produces the smaller value of $E_{w|\varphi}\left[v(a,w)\right]$. Anticipating that the commander will make the optimal decision on receiving forecast φ, by following decision rule $\alpha^*(\varphi)$), we can calculate the expected consequences of receiving a given forecast: $E_{w|\varphi}\left[v(\alpha^*(\varphi),w)\right]$.

Table 6: Decision policy calculations for Halsey scenario.

		$E_{w\|\varphi}[v(a,w)]$, a = 1	2	$a^*=\alpha^*(\varphi)$	$E_{w\|\varphi}[v(\alpha^*(\varphi),w)]$
φ	1	113	124	A	113
	2	48	83	A	48
	3	176	68	B	68
	4	176	26	B	26

3.6 Value of Information

The reference forecast is climatology, denoted φ_R. Conditional on the reference forecast, w is distributed according to its marginal distribution, $P[w]$, given in Table 5 on page 20. The expected consequences of using each missile type, conditional on the reference forecast is
$E_{w|\varphi_R}\left[v(a,w)\,|\,\varphi_R\right]=\sum_{w\in W} v(a,w)\times P[w]$.

Calculating this for each $a \in A$, $E_{w|\varphi_R}\left[v(a=\mathrm{A},w)\right]$=122 and $E_{w|\varphi_R}\left[v(a=\mathrm{B},w)\right]$= 89. The optimal decision, therefore, is always to use Type B missiles, $a^*=\alpha_R^*(\varphi_R)=B$, yielding an expected consequence of 89 Red landing vessels surviving. Since there is only one reference forecast, it is not necessary to take the expectation with respect to the possible values of the reference forecast, and

$$E_{\varphi_R}\left[E_{w|\varphi_R}\left[v\left(\alpha_R^*(\varphi_R),w\right)\right]\right]=E_{w|\varphi_R}\left[v\left(\alpha_R^*(\varphi_R),w\right)\right]=89.$$

However, to calculate VOI, it is still necessary to calculate $E_{\varphi}\left[E_{w|\varphi}\left[v\left(\alpha^*(\varphi),w\right)\right]\right]$, the *ex ante* expected consequences of using the informative forecast φ, i.e. before the forecast is issued. Because METOC outcomes are discrete, the formula is calculated as follows:

$$E_{\varphi}\left[E_{w|\varphi}\left[v\left(\alpha(\varphi),w\right)\right]\right]=\sum_{\varphi\in\Phi}\left(P[\varphi]\times\sum_{w\in W}\left(v\left(\alpha(\varphi),w\right)\times P[w\,|\,\varphi]\right)\right)=77.$$

Following Equation (2), the VOI is 89–77 = 12. In other words, having the forecast reduces the expected number of Red landing vessels that will survive the missile battle from 89 to 77, and the information contained in the forecast allows the disabling of 12 Red landing vessels, in expectation.

This does not necessarily mean that in every possible METOC outcome, the number of Red vessels surviving will be decreased because of the availability of a METOC forecast. In the absence of a forecast, the reference forecast will lead the Blue commander to choose Type B missiles. With the forecast, the commander will choose Type B missiles only if the forecast is $\varphi=3$ or $\varphi=4$, and she will choose Type A missiles if the forecast is $\varphi=1$ or $\varphi=2$. If she chooses Type A missiles, and the METOC outcome is $w=1$ or $w=2$, then the decision is retrospectively the better decision.

However, if Blue chooses Type A missiles, and the METOC outcome is $w=3$ or $w=4$, then retrospectively, the commander will wish she had chosen Type B missiles (see Table 4, page 19). However, the probability of regretting the choice of Type A missiles[11] is small enough that, on balance (in expectation), it is better to use the forecast, and choose Type A missiles when the forecast indicates $\varphi=1$ or $\varphi=2$, leading to the disabling of 33 additional Red landing vessels if $w=1$ and 75 additional Red landing vessels if $w=2$.

4 Using and Valuing Climatology

It is less obvious how to use climatology than METOC forecasts, and its effects are harder to see. Forecasts are more precise, more detailed, more geographically specific, and more accurate than climatology. This section describes the role of climatology as an informational input to operational

[11] This probability is 10%, calculated from joint distribution in Table 5 as the probability that φ or 2 and w = 1 or 2.

planning, and how can influence – and adds can value to – operational decision-making and mission outcomes.

4.1 Adding Climatology to Forecasts

Decision modeling for climatology information and measuring the value of climatology information poses special challenges. Decisions that may be influenced by climatology require long lead times – otherwise, the more precise information provided by METOC forecasts would be used to inform the decisions. Moreover, decisions based on climatology are rarely the last decisions that affect METOC-sensitive mission consequences. In general, for any specific mission scenario, there is some flexibility at short (less than 10-day) lead times to adjust the mission and influence METOC-dependent mission consequences.

Only in very unusual circumstances would climatology be the sole METOC information available to commanders planning and executing operations. The current METOC enterprise delivers forecasts – usually detailed, accurate, and mission-specific – at critical lead-times for mission planning and execution, no matter how small the mission. However, when climatology is used together with METOC forecasts, climatology adds mission value:

Climatology + Forecasts > Forecasts Alone

Sections 2 and 3 describe the use of a single forecast – a forecast for METOC conditions verifying at a single time (in the Halsey scenario, the time of the missile exchange) – to inform a single decision (Blue's choice of missile type). Often, however, more than one forecast is issued for a single verification time – for example, a 48-hour forecast may be issued, and the next day at 24-hour forecast may be issued.

Moreover, climatology may be available weeks or months in advance of an operation, and a forecast, applicable to the same verification time and place, is available hours or days before the operation. Both are information sets that condition the probabilities of the same METOC events.

Even when a forecast for the relevant METOC outcomes will be available before last operational decisions, climatology can add operational value in two ways:

1. Climatology conditions probability distributions for later METOC events, so that commanders may be working with sharper and/or more accurate probability distributions weeks or months in advance of the operation than if they did not have climatology.
2. Decisions that are made with long lead-times that may be informed by climatology create the constraints for later decisions that are made on the basis of forecasts. For example, if we do not plan, at a long lead-time, to have a particular asset available in-theater, then in mission execution, alternative courses of action are limited by the non-availability of that asset.

4.2 Forecasts and Climatology as Information Sets

The term "information set" may be applied to either climatology or to a METOC forecast. The treatment of forecasts and climatology is analogous in OR/DA analysis. The only difference is that decisions made using climatology information are usually followed by later forecasts for the same valid period.

Climatology and forecasts may be presented in different formats. For example, a forecast may be issued probabilistically, but often it is issued as a snapshot of near-future METOC conditions, sometimes as a deterministic narrative of the near-term evolution of METOC conditions describing the anticipated behavior of a METOC system.

Climatology is more commonly presented as a mean, and perhaps maximum historical value of a METOC parameter; sometimes climatology describes frequency of specific, usually extreme events, such as a tropical cyclone. Climatology information is rarely expressed in terms of probabilities, but implicitly is interpreted as conditioning the probabilities of METOC outcomes. For example, learning that significant wave heights in November average 12 feet makes a commander assess as substantial the likelihood of waves of 12 feet and higher. On the other hand, given another state of information – that the significant wave heights average 4 feet – the commander would believe waves 12 feet and higher to be fairly unlikely, and act accordingly.

Regardless of whether information is called climatology or a forecast, it serves to condition the commander's probability distribution over future METOC outcomes.

This interpretation of forecasts and climatology is unfamiliar and non-intuitive to many in the METOC community. Figure 3 represents this conditioning effect conceptually. The outer oval represents all possible future states of the ocean and atmosphere. The next oval represents the possibilities after climatology has been received, indicating a particular climatological regime, or indicating the usual conditions for a given time of year. Finally, the smallest oval indicates the possible future states remaining after a forecast has been issued. The forecast provides more information than climatology, by narrowing the subset of possibilities further – but still within the set of possibilities remaining after the climatology occurred. In other words, climatology narrowed the set of possibilities, and the forecast narrowed it further. In Figure 3, this is represented as only a subset of future states being possible – it could also be interpreted as reducing the probability of some possible future states and increasing the probability of others. In other words, the probability distribution (rather than the set of possibilities) narrows.

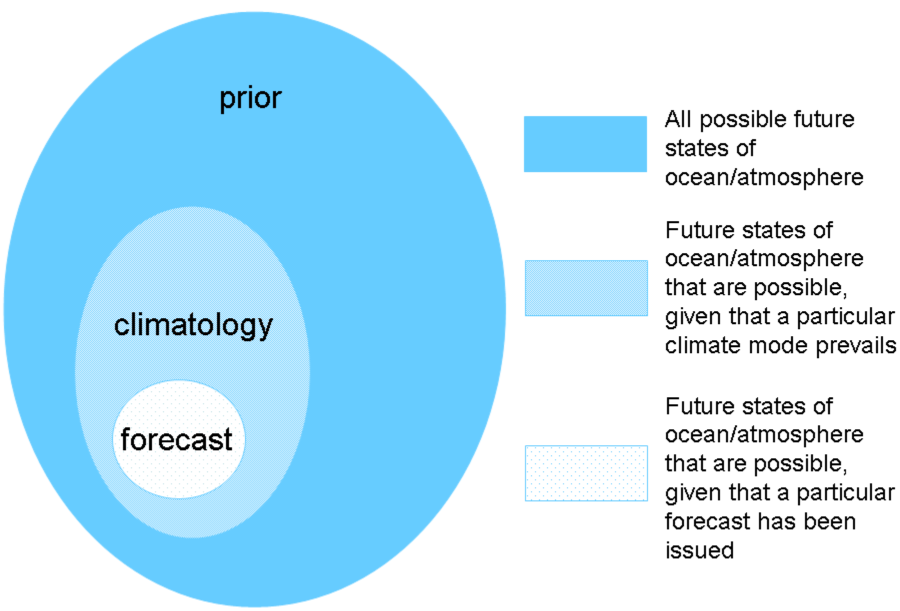

Figure 3: Conceptual representation of conditioning by climatology and forecast information

4.3 Modeling the use of Climatology

In order for climatology to become relevant, the following must be added to the modeled scenario:

- The climatology information set, together with its probabilistic relationship with the forecast information set(s) and METOC outcomes;
- One or more decisions that must be made irrevocably between the receipt of climatology information and the receipt of a forecast and that:

- Are irreversible (or reversible only at significant cost),
- Restrict the range of possible future decisions, OR
- Affect the costs, effectiveness, or other consequences of later decisions or the consequences of METOC outcomes.

More specifically, at each stage that decisions occur (irrevocably), the information set and its probabilistic relationship to prior and succeeding information sets must be modeled. For example, climatology information may be received, and then later forecast information may be received.

To proceed with OR/DA analysis, the minimum modeling of the relationships among information sets and outcomes is (with notation as defined in Table 7):

- $P\left[\varphi_2 \mid \varphi_1\right],\ \forall \varphi_1 \in \Phi_1, \varphi_2 \in \Phi_2$;
- $P\left[w \mid \varphi_1\right],\ \forall w \in W, \varphi_1 \in \Phi_1$, <u>and</u> $P\left[w \mid \varphi_2\right]\ \forall w \in W, \varphi_2 \in \Phi_2$; and
- $P\left[\varphi_1\right],\ \forall \varphi_1 \in \Phi_1$.

The above can assessed separately or can be derived from a complete joint probability distribution over φ_1, φ_2, and w. It is also possible for the two information sets to relate to different METOC outcomes or outcome variables, such that w_i and W_i would be modeled for multiple METOC events indexed by i; the climatology data set will add value as long as there is at least one decision made that meets the requirements bulleted above.

Table 7: Notation for modeling multi-stage decisions

A_i	the set of all alternatives (courses of action) available at stage i in the decision process, $i = 1,...,n$
a_i	the alternative, $a_i \in A_i$ selected at stage i
W	the set of all possible METOC outcomes, relevant to a given decision context
w	a single METOC outcome that may prevail, $w \in W$. w may be multi-dimensional, reflecting multiple METOC variables and/or METOC conditions at multiple decision-relevant times or geographic locations.
Φ_i	the set of all states of information possible in the i^{th} stage, $i = 1,...,n$. Multiple decisions with the same information can be modeled as a single choice, and likewise multiple informational messages received without intervening decision opportunities can be modeled as a single message. Therefore, information opportunities are matched with decision stages. If the first information set is climatology, Φ_1 may be denoted Φ_C
φ_i	a single realization of the state of information at the i^{th} decision stage (equivalently, the i^{th} information opportunity), $\varphi_i \in \Phi_i$.
$v(a_1, a_2, ..., a_n, w)$	a scalar measure of the consequences of the selection (and implementation) of alternatives a_1 through a_n and the occurrence of METOC outcome w
$\alpha_i(a_1,...,a_{i-1},\varphi_i)$ or $\alpha_i(a_1,...,a_{i-1},w_1,...,w_j,\varphi_i)$	a decision rule (policy) that describes the alternative the commander will select if forecast φ_i is issued; may be dependent on the prior alternatives selected. In a further elaboration, $\alpha_i(\cdot)$ may be modeled as dependent on METOC outcomes in some dimensions. In this case, $w_1,...,w_j$ occur <u>and the commander knows their outcomes</u> before decision a_i must be made.
$\alpha_i^*(a_1,...,a_{i-1},\varphi_i)$	The normative (optimal) decision rule; in general, must be found using backward induction, as described in Section 4.4. Therefore, a formula is not provided.
$\Phi_{R,i}$	The set of all possible reference forecasts available at the time of decision a_i .
$\varphi_{R,i}$	A single reference forecast, $\varphi_{R,i} \in \Phi_{R,i}$.

The decision(s) made before receipt of forecast information require modeling – at least two decisions (one made with only climatology information, one made after receipt of a forecast) must be modeled.[12] Therefore, at least two alternative sets and choices, $a_1 \in A_1$, and $a_2 \in A_2$ must be modeled. The consequences of the mission must be extended such that they depend on all METOC outcomes and all decisions, i.e. $v\left(a_1, a_2, ..., a_n, w_1, w_2, ..., w_m\right)$.

Section 5 will illustrate these modeling steps using the Halsey scenario, and analyze the scenario to estimate the value of climatology information. The remainder of Section 4 describes the analysis of a multistage problem.

4.4 Solving for normative decision policies

In a multi-stage decision problem, a solution consists of a policy that indicates the alternative selected at every decision opportunity and for every possible state of information. For example, in a two-stage problem, the policy should tell us $\alpha_1\left(\varphi_1 = 1\right)$ for each value of φ_1, and $\alpha_2\left(a_1, \varphi_2\right)$ for every possible combination of a_1 and φ_2.[13]

A key feature of multi-stage decision problems is that, in general, it is impossible to determine the best decision at early stages without considering what decisions will be made at later stages – because the (expected) consequences of early decisions depend on the choices that will be made later.[14]

The tropical cyclone evacuation decision for a stationary installation is a classic example of a multi-stage decision: a sequence of updated forecasts provides multiple, interrelated decision opportunities. The choices made at early decision opportunities affects the available alternatives later – for example, if an evacuation is undertaken early, the option to not evacuate is no longer available. There is generally some flexibility left – for example to evacuate a short distance or shelter-in-place – until the storm is immediately upon the location in question. If early decisions are made on the basis of early (and therefore less accurate) METOC forecasts, there will be a tendency to undertake more costly alternatives than necessary. On the other hand, if commanders can wait for improved forecasts, they can undertake evacuations only if later forecasts show a continued or increasing threat. Later evacuations may be expedited and therefore more costly or less thorough evacuations, but there will be fewer total evacuations (because sometimes a TC that appears threatening early on will not affect the location), and lower total costs. This concept is elaborated in Regnier and Harr (2006).

Solution Concept

How do we find the optimal policy? The basic solution concept is to assume the commander will make the right decisions in the future. Solutions are reached by backward induction, starting with the last event(s) in the sequence, and working backwards. For every possible decision situation – every possible forecast and prior alternatives selected – the alternative that optimizes expected consequences (minimizes total cost) is selected and all other alternatives are eliminated. Eliminated alternatives should not influence earlier decisions. Assuming the commander will always make the right decisions, the eliminated alternatives will not be selected. Every uncertain event takes on the expected total cost associated with the

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[12] If there were no flexibility to make any decision after receipt of the METOC forecast, then the forecast would add no value.

[13] This includes combinations in which $a_1 \neq \alpha_1^*\left(\varphi_1\right)$. As discussed in this section, decision stages must be analyzed in reverse order $i = n, n-1, ..., 1$, and therefore when analyzing late-stage decisions, it will not be known which values of $a_1, a_2, ...$ will be optimal.

[14] The Halsey scenario has a special structure such that it is possible to identify the best first-stage decision without anticipating the decisions that will be made later. However, this is not generally true.

possible outcomes of its realization, where expectation is taken conditional on all information to that point.

Details on the solution algorithm are provided in the Appendix B.

4.5 Value of Information

The value of information is the difference between the expected consequences if the commander uses the information whose value is being analyzed, and the expected consequences if the she uses less or no information. As discussed in Section 2.6 and illustrated in Section 3.6, calculating the VOI therefore requires modeling the less informative case, which provides the reference.

When multiple information sets – e.g. climatology and a forecast – are involved in determining decisions and consequences, several reference cases could be considered. A reference case might use some but not all of the information sets available in the full-information case, e.g. forecast but no climatology or vice versa, or neither.

The purpose of this report is to show how climatology may be used in operational planning; therefore, the reference cases may include forecasts but exclude climatology. A further issue is semantic – often the term "climatology" is used to describe a less-informative (reference) case. The reason is that when a forecast is absent a decision-maker might use a long-run average (climatological) description of METOC conditions in place of a forecast. However, this paper uses the term "climatology" to refer to an informative message giving a long-run average (or other statistical parameter) of METOC outcomes, but conditioned on some information about the anticipated METOC events. For example, climatology might be the long-run average conditioned on the anticipation of El Niño mode. The VOI for this climatology would be the difference in expected outcomes if the decision-maker uses the ENSO-conditioned climatology in place of the average climatology with all ENSO modes mixed together.

A naïve analyst[15] might estimate the VOI for climatology by calculating the expected total consequences of using ENSO-conditioned climatology (the more-informative case) with the expected total consequences of using non-conditioned climatology (the less-informative case) without modeling the impact of later forecasts. This would generally overstate the VOI by failing to account for commanders' flexibility to adjust to improved information available closer to the time of the eventual operation. Although this would yield a higher estimate of the VOI for climatology, the unrealistic assumption would undermine confidence in the analysis and therefore fail to demonstrate climatology's value. In estimating the value of climatology, the definition of the reference case is very important.

5 Halsey Scenario with Climatology

This section extends the Halsey scenario described in Section 3 to illustrate the use and value of climatology. As discussed above, in order for climatology to add mission value, there must be a decision that can be made upon receipt of climatology that is not reversible later, when forecasts become available. In this case, the long-range decision that cannot be reversed within the time horizon allowed by a forecast is where to station the bomber fleet.

A climatology is issued three months before the engagement, that describes the mode – El Niño, La Niña, or neither – that is anticipated to prevail. With this information set in hand, Blue must decide where to station its bomber fleet. By the time the preparations for the engagement begin, it will be too late to change the stationing of the bombers; they may be flown from their station if METOC conditions permit.

It is assumed that the rules of engagement allow mining, but only once hostilities have been initiated. Blue has the ability to lay sea-mines in the engagement zone, and its ability to do so depends on how

[15] An analyst trained in METOC science might be naïve in this sense – although he would be highly expert in the physics of meteorology and/or oceanography, he would not trained in or (in general) familiar with the OR/DA approach to modeling information.

close its bomber fleet (which will drop the mines) is to the engagement zone, as well as the METOC conditions prevailing at the bomber station. The rest of the scenario proceeds as described in Section 3. Blue will have the missile alternatives described in Section 3.1 and the forecast for the engagement zone described in Section 3.4. The consequences of Blue's actions and Red's response will be affected by the effectiveness of sea-mining. The stationing of the bombers – determined earlier – and the METOC conditions prevailing at its bomber station may limit the effectiveness of mining operations. The expanded scenario is illustrated in the decision tree in Figure 4, and described in Sections 5.1and 5.4.

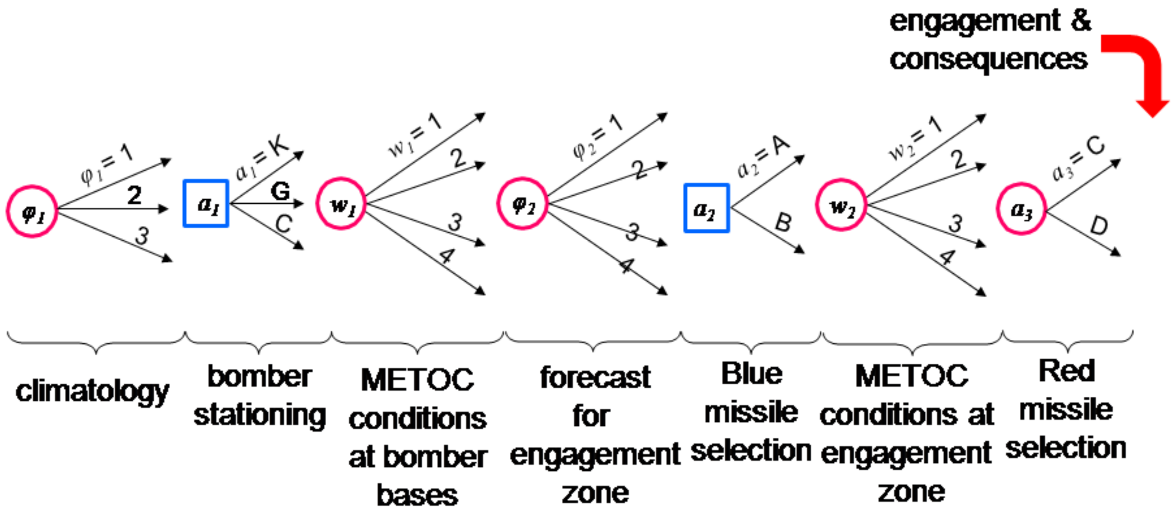

Figure 4: Decision tree for expanded Halsey scenario, from Blue's perspective. Squares represent decision opportunities, while circles represent uncertain events. From Blue's perspective, Red's decision is uncertain. Notation is given in

Table 8.

5.1 Courses of Action

There are two decision points, each having a set of alternative courses of action. The first decision point ($a_1 \in A_1$ must be selected) comes after receipt of climatology, and when the decision is where to station the bombers. The second decision point ($a_2 \in A_2$, formerly $a \in A$) occurs after the receipt of a forecast for the engagement zone. The choice – identical to that described in Section 3.1 – is between Types A and B air-to-surface missile. Table 8 provides notation.

Table 8: Notation for extended Halsey scenario

a_1	The alternative selected at the first decision opportunity, reflecting where bombers will be stationed, $a_1 \in A_1$
A_1	The set of all alternative bomber stations available – Alaksa (A), Kadena (K), and Guam (G), i.e. A_1 ={A,K,G}
a_2	The alternative selected at the second decision opportunity, reflecting choice of air-to-surface missile type for engagement (denoted a in Section 3).
A_2	The set of all alternative missile types available, A_2 ={A,B} (formerly denoted A). Note that in this scenario, the available alternative set does not depend on earlier decisions or outcomes, i.e. A_2 is not a function of a_1, w_1.
W_1	The set of all possible outcomes of the first METOC event, describing conditions at the potential bomber stations, and specifically whether conditions permit bombers to fly from each station.
w_1	The outcome of the first event, indicating which METOC conditions prevail at the time that Red initiates hostilities, $w_1 \in W_1$.
W_2	The set of all possible METOC outcomes in the engagement zone, affecting the performance of Blue air-to-surface missiles (formerly denoted W)
w_2	The METOC outcome in the engagement zone at the time of the missile exchange (formerly denoted w), $w_2 \in W_2$. The outcome w_2 determines which types of Blue and Red missiles will be usable during the missile exchange, as indicated in Table 3, page 18.
$v(a_1, w_1, a_2, w_2)$	The mission-relevant consequences of decisions and METOC events, measured as the number of Red landing vessels that reach the island.
Φ_1	The set of all possible climatologies that could be issued in any year, relevant to the potential bomber stations, in this case modeled as Φ_1 ={ El Niño, La Niña, normal}
φ_1	The climatology issued before the bomber stationing decision is made, $\varphi_1 \in \Phi_1$.
Φ_2	The set of all states of information possible METOC forecasts available for the engagement zone, formerly denoted as Φ in Section 3.4, Φ_2 ={1,2,3.4}.
φ_2	A single possible forecast for METOC conditions in the engagement zone at the time of the mission exchange, $\varphi_2 \in \Phi_2$. Can be interpreted as a categorical forecast of the METOC outcome w_2.

5.2 *Outcomes*

There are now two scenario-relevant METOC outcomes.

5.2.1 METOC conditions in the engagement zone

The METOC outcome $w \in W$ described in Section 3.2 now becomes $w_2 \in W_2$ and determines whether missiles of Type A and B can be used in the engagement zone as indicated in Table 3 on page 18. In addition, when $w_2 = 4$, the length of Red's transit is prolonged. This affects mine-laying but does not affect the outcome of the missile exchange. With the parameter values used, the length of the engagement does not affect the number of Red vessels surviving the exchange, because either Red vessels or Blue aircraft are eliminated within six salvos, with the parameters used here (See Appendix A).

5.2.2 METOC conditions at bomber bases

An additional METOC-outcome variable has been introduced, which reflects METOC conditions at the bomber station. The variable $w_1 \in W_1 = \{1,2,3,4\}$ represents this METOC outcome and is defined in Equation (4) so that it indicates simply whether conditions allow bombers to fly out of each base – details as to why conditions allow or disallow the mission are not modeled.

		Definition
$w_1 =$	1	All Bases OK, 18-hour Red transit
	2	Kadena No Fly, , 18-hour Red transit
	3	Guam No Fly, , 18-hour Red transit
	4	Kadena, Guam No Fly, 36-hour Red transit

(4)

Although the choice as to where bombers will be stationed (a_1) is made before the outcome w_1 is known, the definitions of w_1 and W_1 do not depend on a_1, and reflect conditions at all of the possible bomber stations. Therefore, if bombers are stationed at Guam, $w_1 =1$ and $w_1 = 2$ have identical effects on consequences, as do $w_1 = 3$ and $w_1 = 4$. Note that, according to the model, METOC conditions at the Alaska base will always permit flying – there is no chance that bombers stationed in Alaska may be prevented from operating due to METOC conditions.

5.3 *Consequences*

In the Halsey scenario, the consequence measure has been selected as the number of Red landing vessels surviving to land. This determines the size of the amphibious landing force that reaches the defended island, and therefore reflects the most mission-critical consequence of the mine and missile exchange. Again, as discussed in Section 3.3, the costs of sorties and missiles, as well as mines and mine-removal, are treated as negligible. If these consequences are significant relative to number of Red landing vessels, then they should be quantified and brought in using a multi-attribute measure of consequence.

Under the extended scenario, two stages of Blue decisions and METOC outcomes determine the consequences. Therefore, the notation must be expanded to:

$$v\left(a_1, w_1, a_2, w_2\right) = \text{number of Red escort vessels landing.}$$

The consequences also depend on the Red missile-selection decision. However, it is assumed that Red is able to choose its surface-to-air missile type with perfect information regarding the METOC conditions in the engagement zone, and will choose the missile type that is most effective under the prevailing conditions. Therefore, the METOC outcome, w_2, uniquely determines the Red missile selection, and we suppress notation indicating the dependence of $v(\cdot)$ on Red's decision.

The task at hand is to model the function $v\left(a_1, w_1, a_2, w_2\right)$, which can be represented with a 3×4×2×4 matrix.[16] The modeling of the missile exchange is unchanged, and is described in Section 3.3.

5.3.1 Mining Model

The results of the missile exchange determine the number of Red escort and landing vessels that enter the minefield. Depending how many mines have been laid, some fraction of the Red landing vessels can be expected to be disabled by mines. The remaining landing vessels survive to land.

It is assumed that the mines are laid very close to the landing beach, and therefore, the Red force crosses the mine field after completion of the missile exchange – in other words, Blue aircraft do not continue to strike the Red vessels when they are very close to shore, in the surf zone.

The fraction of Red vessels disabled by the minefield depends on how many mines are laid. It is assumed that the density of mines and the size of the transiting vessel determine the likelihood that a given vessel will be disabled in transit. Specific assumptions regarding the triggering radius and effective radius of the mines, the probability that a single mine will be sufficient to disable a vessel are given in Appendix C. The density of mines is determined by the number of mines that the bomber fleet can drop – which depends on how far the fleet is stationed from the engagement zone, as well as on characteristics of the landing beach and mined area. Assumptions about the landing beach and mined area, as well as the formula for fraction of Red vessels destroyed are given in Appendix C.

The number of mines the bomber fleet can drop depends on how many sorties they can complete before the Red force has transited the engagement zone. The closer the bombers are to the engagement zone, the more round-trip sorties they can complete. If the bombers are stationed at Kadena, they can complete a sortie and be ready to go again in 3 hours, whereas if they are stationed at Guam, the sortie takes 4 hours, and from Alaska, it takes 6 hours. If METOC conditions in the engagement zone are relatively good (w_2 =1,2 or 3), the Red fleet's transit takes 18 hours, meaning that bombers stationed at Kadena could complete 2 sorties, while bombers at Alaska can complete only three before the Red fleet reaches the surf zone. If METOC conditions are poor (w_2 =4), the Red fleet's transit time is 36 hours, which allows proportionately more sorties from each station.

Table 9 shows the results of the mining model, in terms of the fraction of Red vessels disabled as a function of a_1, w_1 and w_2. As expected, stationing at Kadena (a_1 =1) or Guam (a_1 =2) is more desirable when METOC conditions permit flying out of these bases. Alaska is a more desirable location when the transit is long (w_2 =4) than when the transit is short (w_2 =1,2,3).

Table 9: Fraction of Red vessels disabled by minefield, as a function of bomber stationing (a_1) and METOC outcomes (w_1 and w_2).

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[16] There are three possible values of a_1, four possible values of w_1, two possible values of a_2, and four possible values of w_2.

a_1	w_2 =1,2,3				w_2 =4			
	w_1 =1	w_1 =2	w_1 =3	w_1 =4	w_1 =1	w_1 =2	w_1 =3	w_1 =4
1	0.40	0.00	0.40	0.00	0.76	0.00	0.76	0.00
2	0.31	0.31	0.00	0.00	0.61	0.61	0.00	0.00
3	0.15	0.15	0.15	0.15	0.40	0.40	0.40	0.40

5.4 Information Sets

The METOC forecast and event described in Section 3.4 will still be used, but given that an additional information set (climatology) and an additional METOC event (describing the METOC conditions at bomber stations) have been added, the former forecast φ and METOC outcome w are now denoted φ_2 and w_2. The addition of climatology does not change the probabilistic relationship between φ_2 and w_2. Therefore, $P\left[w_2 \mid \varphi_2\right]$ are given in Table 5.

The addition of METOC event w_1, describing the METOC conditions prevailing at bomber stations at the time that Red initiates hostilities was described in Section 0. An additional information set (φ_1) indicates which of three modes – El Niño, La Niña, or neither –is expected to prevail. The climatology would include information about METOC conditions typically associated with each mode – minimum, mean (or mode) and maximum values for key parameters. This information does not have to be modeled to determine decisions, consequences, and therefore climatology value. Rather, the probabilistic relationship between the possible climatology realizations and METOC outcomes is all that is needed to determine decisions. If there were a greater range of possible climatology realizations – if, for example, a climatology could indicate mild vs. severe El Niño, or El Niño with high SST but low wind shear, then the set Φ_1 would have to be expanded to include all possibilities. At the same time, the conditional probabilities of all values of $w_1 \in W_1$, conditional on all possible $\varphi_1 \in \Phi_1$ would need to be estimated. We model $P\left[w_1 \mid \varphi_1\right]$ and $P\left[\varphi_1\right]$ as given in Table 10 below.

In addition, it is assumed that climatology conditions the forecast for the engagement zone. This indicates that certain METOC conditions are more (less) likely under each ENSO mode and therefore forecasts of certain METOC conditions are more (less) likely given the climatology issued. Therefore $P\left[\varphi_2 \mid \varphi_1\right]$ is modeled, as shown in Table 10. The probability distribution is relatively spread out – i.e. the highest valued $P\left[\varphi_2 \mid \varphi_1\right]$ is 0.45, indicating that relatively little uncertainty about the eventual METOC outcomes in the engagement zone can be predicted at the time of the climatology; perhaps a more realistic model would make the climatology even less informative.

Table 10: Probability distributions of climatology, METOC outcomes at bomber bases, and relationship between climatology and forecasts.

	$P[w_1 \mid \varphi_1]$	w_1 = 1	2	3	4	$P[\varphi_1]$
φ_1	1	0.00	0.30	0.10	0.60	0.33
	2	0.65	0.25	0.10	0.00	0.33
	3	0.33	0.28	0.10	0.30	0.33

	$P[\varphi_2 \mid \varphi_1]$	φ_2 = 1	2	3	4
φ_1	1	0.10	0.15	0.30	0.45
	2	0.45	0.30	0.15	0.10
	3	0.25	0.25	0.25	0.25

5.5 Decision Policies

As described in Section 3.5, the decision policies are determined by optimizing expected total consequences in each possible decision situation that might arise. Because more than one forecast (or climatology) might be issued, there are multiple decision situations. A decision policy describes the action that would be selected in every possible situation – for example, for each possible METOC forecast.

As described in Section 4.4, In a multi-stage decision context, the number of decision situations multiplies. For each forecast φ_2, previous events – including the selected value of a_1, the climatology φ_1 and the METOC outcome w_1 – may all affect the optimal decision for a given value of φ_2, hence:[17]

$$\alpha_2^*(\varphi_1, w_1, a_1, \varphi_2) = \min_{a_2 \in A_2} E_{w_2|\varphi_2, a_1, w_1}\left[v(a_1, w_1, a_2, w_2)\right].$$

Earlier decisions (in this example, a_1) are made based only on information available and/or decisions made prior to that time. Therefore, in the Halsey scenario, $a_1 = \alpha_1(\varphi_1)$. As discussed in Section 4.4, we cannot generally write the solution to the early decisions in the form of minimizing the expectation of a single expression – rather, we must solve for these using backward induction. Because of the simple structure of the Halsey scenario modeled, the fraction of ships disabled by the minefield is independent of a_2 and w_2 and depends only on a_1 and w_1. Therefore $\alpha_1^*(\varphi_1)$ simply maximizes the expected fraction of ships entering the minefield that are disabled, where expectation is taken over values of w_1, conditioned on φ_1.

The decision process is illustrated in Appendix B. In this case, it turns out that the optimal decisions

$$\alpha_2^*(\varphi_1, w_1, a_1, \varphi_2) = \begin{cases} \text{A if } \varphi_2 = 1 \\ \text{A if } \varphi_2 = 2 \\ \text{B if } \varphi_2 = 3 \\ \text{B if } \varphi_2 = 4 \end{cases}, \quad \forall \varphi_1, w_1 \text{ and } a_1.$$

[17] The specific structure of the Halsey scenario would allow us to suppress w_1 and a_1 in defining the model, but the solution procedure requires preserving the dependence of $v(\cdot)$ and $a_2(\cdot)$ on w_1 and a_1.

The optimal decisions at the first opportunity, $\alpha_1^*\left(\varphi_1\right)=\begin{cases}\text{Alaska if } \varphi_1=1 \\ \text{Kadena if } \varphi_1=2 \\ \text{Guam if } \varphi_1=3\end{cases}$.

The *ex ante* (before receipt of climatology φ_1) expected number of Red vessels landing is 48.8. It is interesting to note that the climatology associated with the best outcomes (from Blue's perspective) is φ_1=1, which predicts the highest probability of severe METOC in both the engagement zone and the bomber bases. Because in this model Blue's missiles perform in more METOC conditions than Red's, it is to Blue's advantage to have the engagement occur in severe METOC conditions. If Red's decision model were more sophisticated, we might include Red's ability to time their commencement of hostilities to coincide with favorable METOC conditions.

Table 11: Expected total consequences for bomber stationing decision, given optimal missile-selection decision on the basis of later forecasts.

$E_{w_1,w_2\mid\varphi_1}\left[v\left(a_1,w_1,a_2=\alpha_2^*(\cdot),w_2\right)\right]$		a_1 = 1	2	3
φ_1	1	48.6	45.7	42.5
	2	52.9	54.0	64.6
	3	52.3	50.9	53.0

As Table 11 indicates, the difference between the best and worst decisions is greatest for φ_1=2 (a difference of 11.7 Red vessels, in expectation, as compared with a difference of only 2.1 vessels when φ_1=3). As will be illustrated and discussed in the following sections, the VOI may be higher when the variability in outcomes across decisions and METOC conditions is greatest, not necessarily when the consequences are of highest magnitude.

5.6 Value of Information

As discussed in Section 4.5, estimating the VOI requires modeling a less-informative, reference case, identifying what the commander would do, and what consequences would ensue, if she did not have information available. Since we are estimating the value of climatology information in particular, we will consider what the commander would do with neither climatology nor a forecast (Section 5.6.1) and with no climatology, but with a later forecast (Section 5.6.2).

5.6.1 Comparison with no information

If the commander neither received nor anticipated any forecast information she would make both the bomber stationing decision and the missile-selection decision on the basis of the long-run average occurrence of the METOC conditions affecting the consequences of each decision. She would not need to anticipate multiple possible realizations of the forecast information set, but would simply look at the long-run average rate of occurrence of each $w_2 \in W_2$ and each $w_1 \in W_1$ and choose the pair $\left(a_1, a_2\right)$ that produces the best (lowest) expected consequences. Therefore, her decision rule is:

$$\min_{(a_1,a_2)\in\left(A_1,A_2\right)} E_{w_1,w_2}\left[v\left(a_1,w_1,a_2,w_2\right)\right] \tag{3}$$

where the expectation will be taken with respect to the – unconditioned – joint probability distribution of w_1 and w_2, calculated from Table 5 and Table 10,[18] and the consequences given in Table 12 below.

Table 12: Expected consequences of each pair of stage 1 and stage 2 alternatives (a_1 and a_2) and METOC outcomes using unconditioned (marginal) probability distribution of METOC outcomes, w_1 and w_2.

	$E_{w_1,w_2}\left[v\left(a_1,w_1,a_2,w_2\right)\right]$	a_2: 1	2
a_1	1	104	61
	2	99	60
	3	98	64

The optimal decisions, $\alpha_1^*\left(\varphi_{R1}\right)$ and $\alpha_2^*\left(\alpha_1^*,\varphi_{R1}\right)$ are $\alpha_1^*\left(\varphi_{R1}\right)$ =G (Guam) and $\alpha_2^*\left(\alpha_1^*,\varphi_{R1}\right)$ = B, which yield an expected 60.2 Red vessels landing. The VOI is 11.4 vessels = 60.2 – 48.8.[19]

5.6.2 Comparison with forecast only – no climatology

If the commander had forecasts available, but not climatology, her best policy would be

$$\alpha_2^*\left(\varphi_1,w_1,a_1,\varphi_2\right)=\begin{cases}\text{A if } \varphi_2=1\\ \text{A if } \varphi_2=2\\ \text{B if } \varphi_2=3\\ \text{B if } \varphi_2=4\end{cases},\ \forall\varphi_1,w_1,a_1,$$

[20] and the best policy for choosing a_1 would be

$\alpha_1^*\left(\varphi_{R1}\right)=\min_{a_1\in A_1}\left\{E_{w_1,w_2,\varphi_2}\left[v\left(a_1,w_1,\alpha_2^*\left(\varphi_1,w_1,a_1,\varphi_2\right),w_2\right)\right]\right\}$ = G (Guam), for an expected consequence of 50.2 Red vessels making landing. The VOI for forecasts is therefore 60.2 – 50.2 = 10, and the VOI of adding climatology to the forecast is 50.2 – 48.8 = 1.4.

In light of Blue's objective to reduce the expected number of Red vessels making landing, we should anticipate that the expected consequence of having forecasts but no climatology would be greater than in the case with <u>both</u> climatology and forecasts, but less than the case with neither. As summarized in Table 13 below, this is what we find.

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[18] $P\left[w_1,w_2\right]=\sum_{\varphi_1\in\Phi_1}\left(P\left[\varphi_1\right]\cdot P\left[w_1\mid\varphi_1\right]\cdot P\left[w_2\mid\varphi_1\right]\right)$ where $P\left[w_2\mid\varphi_1\right]=\frac{P\left[w_2\mid\varphi_1\right]}{P\left[\varphi_1\right]}$,

$P\left[\varphi_1,w_2\right]=\sum_{\varphi_2\in\Phi_2}\left(P\left[\varphi_2\right]\cdot P\left[w_2\mid\varphi_2\right]\cdot P\left[\varphi_1\mid\varphi_2\right]\right)$, $P\left[\varphi_1\mid\varphi_2\right]=\frac{P\left[\varphi_2\mid\varphi_1\right]\cdot P\left[\varphi_1\right]}{P\left[\varphi_2\right]}$, $P\left[\varphi_1\right]$ and $P\left[w_1\mid\varphi_1\right]$ are given in Table 10, $P\left[w_2\mid\varphi_2\right]$ and $P\left[\varphi_2\right]$ are given in Table 5. The above formulas assume that $P\left[w_1\mid\varphi_1\right]$ and $P\left[w_2\mid\varphi_1\right]$ are independent, and $P\left[w_2\mid\varphi_2\right]$ and $P\left[\varphi_1\mid\varphi_2\right]$ are independent.

[19] The VOI in the two-stage Halsey scenario (11) is close to the VOI calculated for the single-stage scenario (12). This similarity is coincidental – the two-stage scenario is quite different, and adds the possibility of mining the surf zone. The expected number of Red vessels making landing is thereby reduced, and there is no clear relationship between the VOI in the two scenarios.

[20] The fact that $\alpha_2^*\left(\cdot\right)$ does not depend on φ_1,w_1 and a_1 is an artifact of this scenario; in general, there could be a dependence.

Table 13: Value of Information and expected consequences using no information, forecasts only, and forecasts with climatology.

	$E\left[v\left(a_1, w_1, a_2, w_2\right)\right]$ Expected Red vessels landing	VOI relative to no information	VOI relative to forecast only	VOI relative to climatology only
Both forecasts and climatology	48.8	11.4	1.4	9.9
Forecast only	50.2	10.0	–	–
Climatology only	58.7	1.6	–	–
Neither forecast nor climatology	60.2	–	–	–

The value contributed by climatology (1.4 Red vessels) over and above the value of METOC forecasts is small, relative to the value contributed by forecasts (10 Red vessels). This result is specific to the Halsey decision and engagement model used here, and may not represent the general relative importance of METOC climatology and forecasts. However, we should expect the incremental value of climatology used in conjunction with forecasts to be lower than the value of forecasts themselves. Forecasts are more accurate, and therefore provide more informational value. Moreover, the value of climatology is properly calculated as an addition to the value of forecasts – if forecasts were not available, the value of climatology would (usually, but not necessarily) be substantially higher than its value in conjunction with forecasts. In addition, it should be considered that this is in expectation, and in certain scenarios will be much higher.

5.6.3 Comparison with climatology only – no forecast

The value of adding climatology only to the no-information scenario may also be calculated. This describes a scenario in which the commander does not receive any forecast for METOC conditions in the engagement zone and therefore use long-run average frequencies of the METOC outcomes ($P\left[w_2 \mid \varphi_1\right]$) to make the missile-selection decision (a_2).

The commander would not need to anticipate multiple possible realizations of the forecast information set, but would simply look at the long-run average rate of occurrence of each pair $\left(w_1, w_2\right)$ given φ_1, and choose the pair $\left(a_1, a_2\right)$ that produces the best (lowest) expected consequences. Therefore, her decision rule is:

$$(\alpha_1^*, \alpha_2^*) = \min_{(a_1, a_2) \in (A_1, A_2)} E_{w_1, w_2 \mid \varphi_1}\left[v\left(a_1, w_1, a_2, w_2\right)\right] \text{, a function of } \varphi_1 \quad (3)$$

The results are $\alpha_1^*\left(\varphi_1\right) = \begin{cases} \text{Alaska if } \varphi_1 = 1 \\ \text{Kadena if } \varphi_1 = 2 \\ \text{Guam if } \varphi_1 = 3 \end{cases}$, and $a_2^* = 2 \ \forall \varphi_1 \in \Phi_1$, with corresponding

$$E_{w_1, w_2 \mid \varphi_1}\left[v\left(\alpha_1^*\left(\varphi_1\right), w_1, a_2 = 2, w_2\right)\right] = \begin{cases} 48.6 \text{ if } \varphi_1 = 1 \\ 66.0 \text{ if } \varphi_1 = 2 \\ 61.4 \text{ if } \varphi_1 = 3 \end{cases}.$$

The expected total consequences (with expectation taken over φ_1) is 58.6, meaning the VOI of climatology only in the Halsey two-stage scenario is 1.6. When evaluated conditioned on specific values of φ_1, however, the value of climatology is higher. When φ_1 =2, climatology does not affect a_1 and therefore has no value, as defined with the VOI framework. On the other hand, when φ_1 =1 or 3, climatology will induce the commander (if she behaves optimally) to change her bomber stationing decision. In the case of φ_1 =1, this increases the chances that mining will be possible – because bombers will be flown out of Alaska, reducing the expected number of Red vessels landing from 51.8 to 48.6 (a difference of 3.2). In the case of φ_1 =3, stationing bombers at Kadena rather than Guam increases the number of sorties that can be completed in the (relatively likely) event of permissible METOC conditions for flying, thus reducing the expected number of Red vessels landing from 64.2 to 61.3, a difference of 2.8.

6 Value Insights

This section describes and illustrates – using the Halsey scenario and other examples – factors that generally increase (or decrease) the VOI contained in forecasts, ending (Section 6.4) with a discussion of the VOI for early forecasts (or climatology) when there are also later forecasts.

6.1 How alternatives affect value

The type of alternatives available and the way these alternatives mediate the impact of METOC conditions are a major determinant of the value of forecast information. As discussed earlier, the common assumption that information is always valuable and that more accurate forecasts always add value may not necessarily hold. The value of forecasts depends what can be done **in response to** the information they contain – in other words, forecast value depends on the alternative courses of action available.

6.1.1 Decision-sensitive consequences

Information provides greater value when decisions substantially influence outcomes – i.e. for a given METOC outcome, there is a significant difference in consequences depending on which course of action is selected

Depending on the decision context, consequences may be METOC-sensitive but not decision-sensitive or vice versa. **When consequences are METOC-sensitive but not decision-sensitive, even highly accurate METOC forecasts of operationally relevant parameters may be of low value – and in some cases should even be ignored by rational decision makers.** A classic example is when severe METOC conditions are threatening to life and health (i.e. consequences are highly METOC-sensitive) – but there is little or nothing to do about it. In the Halsey scenario, if commanders learned 24 hours before their mission that there is a high probability of a tropical storm affecting Guam and Kadena, it would be too late to re-station the bombers. At this point, there is no remaining alternative but to wait and see if METOC conditions will permit flying, and there is no value to seeking the 24-hour forecast for the bomber stations.

A similar situation occurs when alternatives are available, but alternatives that would affect METOC consequences – e.g. protect life and health are as costly as the potential METOC damages themselves. For example, if the consequences of failing to complete a mission are so severe that it is worthwhile to incur substantial risks, then METOC forecasts may be ignored. Even if the forecaster is very confident that conditions will be adverse, the mission may proceed – and METOC information has little or no value. Rules that allow president-ordered operations to proceed even when operational thresholds for METOC and other conditions are violated demonstrate that sometimes the value of even a small probability of mission success is enough to outweigh METOC-related risks. By contrast, for low-value missions, METOC information (climatology or forecasts) may be highly valuable because small differences in METOC conditions will drive decisions.

6.1.2 Flexibility

Information provides greater value when decision makers have flexibility – i.e. more alternatives (generally) mean more value. We can even make the stronger statement that, if the decision maker behaves normatively, the addition of an alternative cannot lower VOI, all else remaining unchanged.

A simple intuitive explanation of this relationship is that the more alternatives are available, the more the selected alternative will be fine-tuned to the METOC forecast. At the limit, if there are no alternatives – i.e. the decision-maker has no decisions to make – then information has no value, as discussed earlier.

Factors that contribute to flexibility – and therefore to higher value for forecasts – include:

- **Mobile assets** (geographic flexibility) – when forecasts are good, mobile assets can be moved to follow desirable METOC conditions. Commonly, this is operationalized when valuable assets are moved to avoid adverse conditions that might damage them – for example, aircraft are moved when severe METOC is expected, and ships are routed to avoid high seas. Value arises from the prevention of damage.

  More generally, when it is possible to conduct METOC-sensitive operations (or store METOC-sensitive assets) in multiple locations, METOC forecasts are highly valuable in identifying locations with desirable conditions.

- **Timing flexibility** – the ability to move up or delay an operation means that METOC-sensitive activities can be conducted during times when METOC conditions are more suitable (relative to what they might be if timing were fixed).

  This has the counterintuitive result that METOC forecasts may be more valuable for routine missions than for more important missions. Less-critical missions, such as training, generally have more timing flexibility than critical missions. If the mission is extremely urgent (as in search-and-rescue) or has a very narrow time window, then the mission will go ahead regardless of METOC forecast and METOC conditions.

  A few hours' wiggle room may be enough to exploit the value of METOC forecasts – in the planning for D-Day in 1944, the flexibility across just a few days allowed the Allies to exploit a small window in METOC conditions.

- **Short response times** – if there are multiple alternatives that can be selected with short lead times before the relevant METOC events, more flexibility is preserved until late in the operational planning. As forecast accuracy generally improves as lead time declines, short response times allow for decisions to be made with better information – resulting in (on average) better outcomes. For example, if a decision must be made with a 24-hour lead time, a 12-hour forecast may not have value.

  A related concept – (ir)reversibility – is important when there are multiple forecasts for a single event (e.g. when climatology is available, followed by a forecast or forecasts). Reversibility has an ambiguous relationship with value, as discussed in Section 6.4.

6.2 METOC sensitivity

The range of METOC outcomes and the relationship between consequences and METOC outcomes are related to the VOI – in both expected and unexpected ways.

6.2.1 METOC-sensitive consequences

Forecasts are more valuable when consequences are substantially different as a function of the METOC outcome. In other words, if METOC conditions have a big impact, it is (generally) more important to have accurate information about METOC conditions – all other things being equal. An important qualifier is that there have to be alternatives, available **after** the receipt of a forecast, to alter the METOC consequences (see Section 6.1).

6.2.2 Variability in METOC conditions

A corollary to the previous insight is that a high degree of variability in METOC outcomes tends to raise the value of information. Variability in this case means a wider prior distribution of outcomes, which is distinct from predictability.

An intuitive explanation is that, when METOC conditions are highly variable, conditions suitable for each alternative are relatively likely to arise – by contrast, when METOC conditions are very stable, the alternative most appropriate for the common conditions will usually be appropriate, and only rarely would forecasts indicate that this should change.

However, this relationship is even stronger than the preceding explanation indicates. **When METOC conditions are more variable, rational decision-makers should give more weight to forecasts than when METOC conditions are more stable**. In normative decision-making, the choice of an alternative should be driven by the probability distribution of METOC outcomes conditional on the forecast message received. When the climatological variability is low, the probability of extreme events will be lower, conditioned on each possible forecast.[21] A related effect is elaborated in the following section.

The relationship between variability and value is, however, context dependent. In considering submarine detection problems, for example, it may be that it is better to search in a region that has a high degree of variability in detection conditions than in a region with better average conditions, but lower variability. In a search problem, for example, multiple opportunities for detection occur, and if the enemy submarine passes through a high-detectability region once, this may be enough to allow its detection. High-detectability may be more common in a high-variability region with worse average conditions than in a low-variability region with better average conditions.

6.2.3 Base rate of adverse METOC events

When the base rate, or long-run average (climatological) frequency of a critical METOC outcome is very low, then the value of a METOC information system is low. This is caused by two factors:

1. If the critical outcome occurs infrequently, opportunities for METOC information to influence decision-makers to prepare for the critical outcome are rare, and therefore, the long-run average value contributed by the METOC information will below; and
2. If the base rate for the critical outcome is low, then the probability of the critical outcome occurring – even conditional on the issuance of a forecast of the critical outcome – is relatively low. This would hold even for highly accurate forecasting systems. Therefore, a decision-maker might rationally choose to plan for other, more likely, outcomes. From the forecaster’s perspective, this could be interpreted as the decision-maker ignoring the forecast. The value of the forecast would therefore be low.

Like the other value insights, the effect of base rate applies when all else is held constant. In a situation where the decision is very sensitive to the METOC conditions, or the ability of decisions to affect the impact of the critical METOC outcome is very high, then forecast information may be highly valuable, even if the base rate for the critical METOC outcome is low. Tropical cyclone forecasting is a good example – although the frequency of tropical cyclone conditions at any given location is relatively low, the consequences of failing to prepare for the storm are so severe, that decision-makers will want to act on forecasts even though the base rate – and therefore the probability of critical METOC conditions conditional on the issuance of a forecast of tropical cyclone conditions – is relatively low.

[21] This basic relationship implies that forecasters should regress to the mean when METOC conditions are relatively stable. Human forecasters rarely do.

6.3 Forecast Sensitivity

6.3.1 Accuracy and Value

Generally, greater accuracy leads to greater value – because it is less likely (less frequent) that the forecast errs, leading decision-maker to select an alternative that is not appropriate for the actual METOC conditions.[22]

However, this general result is subject to the effects of METOC-sensitivity and alternative-sensitivity of the consequences. There may be ranges over which increases in accuracy do not affect value, as, for example, when there are METOC conditions over which a single alternative is best – forecasts that are highly accurate at discriminating among these outcomes are valueless.

6.3.2 Decisions are highly sensitive to forecast in the range of likely forecasts

Information provides greater value when the range of possible forecasts includes information sets that would induce substantially different courses of action. In other words, all other things being equal (even if the consequences of a bad METOC outcome or a retrospectively bad decision are severe), if there is a high prior likelihood that the forecast will induce a given decision, then there is less value to the forecast.

If, on the other hand, likely forecasts would tip the decision sometimes one way and sometimes the other, then the forecast has greater value. This can occur, for example, if forecasts frequently (or likely) occur on each side of a threshold.

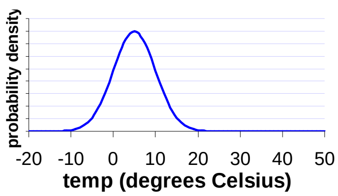
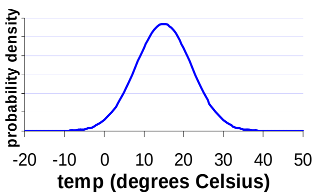
To see how this works, consider a simple cost:loss decision model, under four decision scenarios, depicted in

[22] We could even say that *if decisions are made rationally* (optimally), *increasing accuracy can never decrease VOI*, unless increasing accuracy leads to less informative forecasts – e.g. if we are starting with a forecast that's always wrong (and therefore highly informative!).

Table 14 below. There are two critical thresholds – these could reflect two different types of mission. For example, icing may occur if ground temperatures are <0°C, so flights are dangerous; heat stroke is a high risk if temperatures >20°C, so field training should be cancelled. There are also two probability distributions of the actual temperature – perhaps the first represents January and the second represents April. Assume a perfect forecast is available, and in the absence of the forecast, the mission would always proceed.

Why does this occur? Information helps decision-makers to know when to cancel the mission and avoid incurring the loss. For the flying mission, this occurs when the temperature (and therefore the perfect forecast) will be less than <0°C. This occurs 13.5% of the time under the first probability distribution, and only 1.3% under the second probability distribution. In April, ignoring the forecast means the probability of icing conditions is only 1.3% - a much smaller risk. Similarly, for the field training mission, the probability of exceeding the threshold >20°C is less than 0.1% for the January probability distribution, and 21.5% for the April probability distribution. In January, the training commander can afford to ignore the forecast, but in April, ignoring the forecast would mean running a substantial risk.

Table 14: Effect of interaction between operational value and probability distribution over METOC outcomes. Values give the VOI for each scenario, assuming cost = 1 and loss = 10.

		Critical Temperature	
		<0°C	>20°C
Probability distribution of temperature outcomes		1.27	0.12
		0.01	1.94

It is not simply the threshold or the base rates that determine the value of the forecast, but the intersection between the two.

6.4 Climatology

Information provides greater value when decisions are difficult or impossible to undo. Because climatology information is available at long lead-times, there may be a wide scope for operational decision-making at climatological lead times. For example, climatology may allow commanders to move the timing of an operation up or back by weeks or months, rather than days or hours, and to move assets into or out of a theater. On the other hand, these decisions and their implementation may be reversible, possibly at some cost. The ability to reverse or undo previous actions (see flexibility in Section 6.1.2) generally declines (or cost of reversing increases) as lead time declines.

The key to VOI is the relationship between receipt of information and loss of reversibility (flexibility). As discussed and illustrated in Section 5.6, the VOI for climatology depends on the METOC forecasts that will be received later, and how much flexibility will remain once METOC forecasts are received. The more flexibility that remains later, the less value climatology will contribute.

Long lead-time decisions that may be informed by climatology generally create the constraints for short lead-time decisions that can make use of METOC forecasts. Long lead-time decisions may determine the decision context, i.e. what alternatives are available (example: where are bombers stationed), how much impact those alternatives will have (e.g. by having reduced impact of bad outcomes or cost of protective actions). Long lead-time decisions may also influence short-lead decisions by affecting the likelihood of METOC forecasts and outcomes. The simplest example is that climatology could influence planners to plan an operation for a given time period or geographic location where conditions are likely to be most favorable.

In addition, when there are multiple forecasts (or climatology plus at least one forecast) and where alternatives include the ability to collect data to inform future forecasts, then early forecast have more value. The early forecast enables decision-makers to increase the forecast accuracy and/or the tailoring of the forecast for the relevant decision by collecting observations that reduce the uncertainties that are most critical to the decision at hand.

7 Challenges

An OR/DA approach, and the VOI tool, can be tremendously valuable in analyzing METOC information systems – including both forecast and climatology. As discussed in Section 1, VOI can serve the METOC enterprise in many ways, not least by quantifying the value of METOC services, and by guiding the design of new or improved METOC information systems (to maximize their value). However, there are a number of important challenges to effective use of OR/DA in this context.

7.1 Modeling and measuring the value of METOC information

This report has illustrated the estimation of the VOI for METOC information using with a highly stylized example – the Halsey scenario. The use of several simplifying assumptions in the Halsey scenario model points to some of the challenges to using the OR/DA framework to model a real operational context.

7.1.1 Modeling METOC

Modeling the probabilistic relationships among multiple stages (climatology, forecasts, outcomes) and multiple variables is essential to a VOI analysis. The probability of every possible state of information and the probability of every outcome, conditional on each state of information must be modeled. The simplest case a single-stage decision with one forecast and one METOC outcome variable – is described in Section 2.4.

In many situations, information and/or outcomes may be **multi-dimensional**. For example, for flight operations, two operationally relevant variables are cross-winds and visibility. Therefore, both of these variables should be forecast, and the outcomes of both determine the operational impacts. In general, the two variables will not be independent – e.g. for cross-winds and visibility, a positive correlation would be expected. Therefore one of the simplest models of the probability distribution of the states of information would be a bivariate normal distribution, which would require estimation of five parameters.

The model also requires the probability of every METOC outcome, conditional on each state of information. Again, a relatively simple model is a multi-variate normal distribution, which again requires the means of each of the four variables, plus the covariance matrix (ten independent parameters).

Moreover, there may be **multiple decision stages**. It is not realistic to model the use of climatology in a single-stage decision. As discussed above, it is hard to imagine a scenario in which only climatology information is used to make operational decisions, and no decision flexibility remains when later, more detailed METOC forecasts become available.

The profusion of variables and parameters required to estimate the probability model grows quickly when multiple stages are added, as when climatology is involved.

The modeling requirements will demand either **large historical data sets of both forecasts and METOC outcomes**, or substantial simplifying modeling assumptions.[23] The data demands depend on many factors, but increase exponentially in the number of operationally relevant METOC variables, the number of time periods involved in decision-making for a given mission and the number of METOC information sets relevant to a given valid period. In general, the preservation of historical forecast data is not intended to support OR/DA modeling – and therefore too little data (from the perspective of OR/DA) is preserved. There are several of reasons for the lack of data: the decisions about what to collect were not made with the needs of OR/DA analysts in mind; the amount of potentially useful data is much greater than existing storage capacity; and as forecasting models and techniques change, data arising from obsolete models/techniques may be considered obsolete.

[23] Even if there is a great deal of data, the probability model will still be a model, not a perfect representation of the ocean-atmosphere-information system

Expertise gaps, as well as data availability, contribute to making the probabilistic modeling of METOC information challenging. Moreover, data and expertise are complementary. The fewer data are available, the more important multivariate, time-series statistical modeling becomes. Few people are familiar with both the METOC models and the statistical techniques required.

Data and expertise limitations for OR/DA are discussed at greater length in Regnier (2007) and Regnier (2008b).

This report focuses on measuring the VOI of an existing METOC system. However, one of the most powerful applications of VOI analysis is in designing new and improved climatology or forecasting systems. The basic approach is to

1. model the operation and consequences; then
2. model multiple hypothetical (design) METOC information systems;
3. identify the decision policies that would be appropriate for a user with each hypothetical system;
4. calculate the VOI for each system; and
5. compare – the higher VOI indicates the more effective system.

Step 2 above is to model multiple hypothetical METOC information systems – each has the modeling requirements described earlier in this section. The challenge of creating these models is substantial.

7.1.2 Modeling consequences of METOC outcomes

Modeling the consequences of METOC outcomes is a further challenge – and is even less familiar to the METOC community. In order to use OR/DA to assess information systems, it is necessary to model all available alternatives that may be selected by a decision-maker using METOC information. It is also necessary to model how both METOC conditions and decisions made on the basis of METOC information affect operational consequences $v(a,w)$, depicted in Figure 1b. Both alternatives and consequences should be modeled quantitatively – this is well outside the scope of responsibility of METOC experts.

In addition to the barriers posed by the domain responsibility, this kind of modeling is difficult in large part because relevant data are not collected. One of the reasons is that there is no responsible party. Operators worry about controlling consequences as much as they can, and do not necessarily have a use for information about quantitative relationships between METOC and consequences. They also are cognizant of many factors other than METOC influencing consequences. The METOC community – including both researchers and forecasters – is not generally familiar with operations and consequences, and do not generally think of the relationship between METOC and consequences as part of their responsibility.

Even if the responsibility were undertaken, quantifying mission consequences, and modeling how mission consequences depend on METOC outcomes is very difficult. Mission consequences are multi-dimensional, and often assessed subjectively.

The role of METOC information in helping commanders to make decisions that lead to the best mission results, an analyst must understand what would happen if the commanders took other courses of action – these consequences, though never observed, must be modeled. If decisions are determined in a rule-based way, often certain combinations of decisions and METOC outcomes are not observed – therefore data are not there to collect.[24]

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[24] In the analysis of platforms and weapons systems, even those that are METOC-sensitive, the effects of METOC are usually treated as threshold-based limits. In testing and evaluation, METOC impacts are usually not tested, at

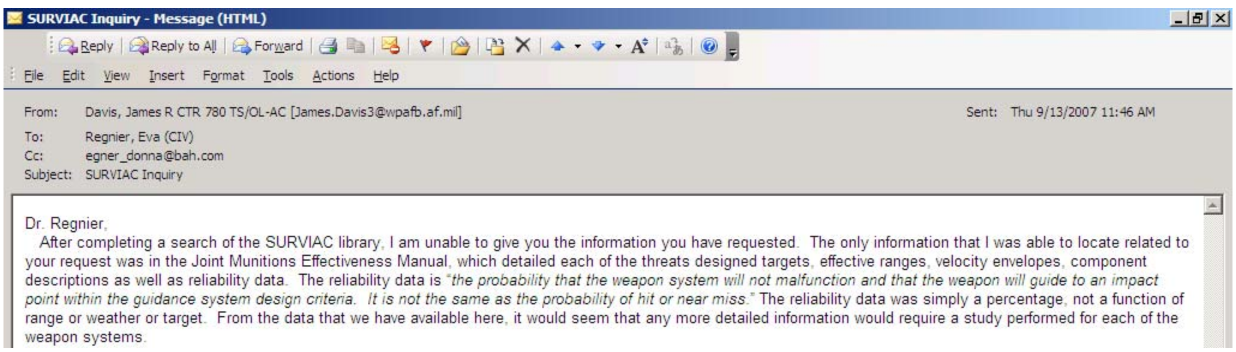
Moreover, when commanders retrospectively assess operations, they generally emphasize contributions to mission success over which they had control – and generally ascribe less importance to aspects like METOC conditions over which they had no control. Therefore, even when METOC conditions affect mission results, the impacts are rarely quantified and reported.

All of these challenges are especially difficult for modeling or collecting relevant data for modeling the use and impact of climatology information. Climatology-based decisions and their consequences are separated in time attenuating both responsibility and causal relationships.

METOC impacts on weapon systems

I pursued public, private, and classified routes to try to find information on the effect of METOC operations on missiles and mines. I looked into the assumptions behind mine-warfare tactical decision aid. I tried to identify academic experts in the mechanics of sea mines. At least one expressed the belief that high seas would increase mines' effective radius, and at least one believed the opposite.

I tried common sources on weapons information – such as Jane's, wikipedia (which was surprisingly informative) – and DoD sources, such as JMEMS (Joint Munitions Effectiveness Manuals). I contacted the Survivability/Vulnerability Information Analysis Center (SURVIAC), "the DoD's institution for collecting, analyzing, and disseminating scientific and technical information (STI) related to all aspects of survivability and lethality for aircraft, ground vehicles, ships and spacecraft, to conventional homeland security threats including chemical, biological, directed energy, and non–lethal weapons" (http://www.bahdayton.com/surviac/). A typical response is shown below.


SURVIAC Inquiry - Message (HTML)

Reply | Reply to All | Forward

File Edit View Insert Format Tools Actions Help

From: Davis, James R CTR 780 TS/OL-AC [James.Davis3@wpafb.af.mil]
Sent: Thu 9/13/2007 11:46 AM
To: Regnier, Eva (CIV)
Cc: egner_donna@bah.com
Subject: SURVIAC Inquiry

Dr. Regnier,

After completing a search of the SURVIAC library, I am unable to give you the information you have requested. The only information that I was able to locate related to your request was in the Joint Munitions Effectiveness Manual, which detailed each of the threats designed targets, effective ranges, velocity envelopes, component descriptions as well as reliability data. The reliability data is "*the probability that the weapon system will not malfunction and that the weapon will guide to an impact point within the guidance system design criteria. It is not the same as the probability of hit or near miss.*" The reliability data was simply a percentage, not a function of range or weather or target. From the data that we have available here, it would seem that any more detailed information would require a study performed for each of the weapon systems.

Because of the challenges in measuring, modeling, or otherwise attempting to predict the performance effects of various METOC conditions, the lack of information I encountered for weapons systems may also extend to other systems, such as sensing equipment, aircraft and seacraft.

In at least some cases, manufacturers offer standards for METOC conditions under which their systems may be used. For example, this information may be provided in the NATOPS (standard operating procedures) documentation.[25] Certainly, the DoD organizations that fly aircraft have standards for the METOC conditions that permit flying. However, these are not based on measuring the impact of varying METOC conditions on performance measures, such as probability of successful takeoff or landing. For

least not at multiple levels. By contrast, the OR/DA approach would involve analytically identifying an optimal threshold, which balances risk of adverse METOC conditions with the risk of failing to take advantage of acceptable METOC conditions. Moreover, the optimal threshold would change as a function of specific details of a mission – to include how critical the mission is in the larger context. In practice, these thresholds have generally been identified subjectively, are fixed for all missions that involve particular platforms or weapons systems, and are unlikely to be "optimal" in any given set of circumstances.

[25] I initially tried to get a copy of this document for an F-18, or at least of the relevant sections, but it is not available for free, and I talked with some pilots, and am basing this on their description of the type of information provided. One route to purchase a NATOPS is http://rareaviation.com/store/catalog/product_2801_NATOPS_Flight_Manual_for_Navy_Model_F_A18E_F_Aircraft_cat_888.html.

obvious reasons, measuring this relationship experimentally would be costly and dangerous. Modeling METOC impacts on systems is also likely to be costly and difficult (for a modeling effort) and perhaps not worthwhile.

7.2 Design of forecast and climatology systems to support decision-making

There is a chicken-egg problem in the design of forecast and climatology systems to support operational decision-making. Users have neither decision processes nor models for hypothetical future systems, and therefore cannot inform design by saying what they need. The METOC community does not know the details of how information may be used and what the operational impacts might be, and so cannot design optimally. Before a hypothetical METOC product, or product enhancement such as increased accuracy, becomes available, end-users have no incentive to identify ways to use the product, let alone predict the consequences of its use. Many potential applications will not be identified until the required information product is provided to commanders. Even once a product is available, it may take some time for commanders to gain familiarity with and confidence in the product and begin to use it.

Figure 5 expands on the influence diagram in Figure 1 by depicting in pink elements of the METOC information and decision-making systems that influence forecast value over the long term. On the METOC side, investments in observing systems, modeling, and data collection and storage affect the quality, quantity, lead time and type of guidance available to forecasters. Forecast methodology – the processes by which forecasters integrate guidance to produce forecasts – affects both forecast accuracy and the format of forecast information. Examples of changes in forecast methodology include training to improve forecaster judgments, automation of some portion of the forecast process, and development of new products that may be tailored to specific users or decisions.

Improvements in any of these elements should make METOC information more accurate, which in turn should affect how users exploit forecast (or climatology). In general, the more accurate the information, the more decisions should be influenced by it, and the more value can be extracted by using the information as a decision input. New forecast products and improved product design can also increase the value of METOC information by increasing the number of decisions that can be based on the information – for example, redesigning a threshold-based product around an operationally relevant threshold could increase the product's value (see Section 6.3.2), even if accuracy does not improve.

This highlights the interaction between changes on the METOC side and changes in the decision context. The development of decision policies has been modeled in this report as commanders' means of exploiting METOC information to produce the best expected outcomes. Decision policies may dictate what information should be included in a decision process, as well as what alternatives should be selected, conditional on METOC information. As METOC information content and quality changes, so decision policies should change. For example, if tropical cyclone track forecasts improved dramatically, the conditions for setting TCCOR 4 might be limited – perhaps TCCOR 4 would be set only when tropical cyclone formation potential was above some threshold.

As indicated in Figure 5, over the long run, commanders may also be able to change the alternatives available to them. For example, in the Halsey scenario, if Blue were able to acquire missiles that require different METOC conditions from the Type A and B missiles, and/or have different costs and effectiveness, the decision policy would change to reflect the new alternatives, and the value of METOC information would change, and possibly increase.

The elements of the METOC system represented in pink in Figure 5 (observation, modeling, and climatology data systems and forecast methodology) are often analyzed independently of the elements of the decision context (decision policy and available actions) and vice versa. However, their effects on forecast value are highly interdependent.

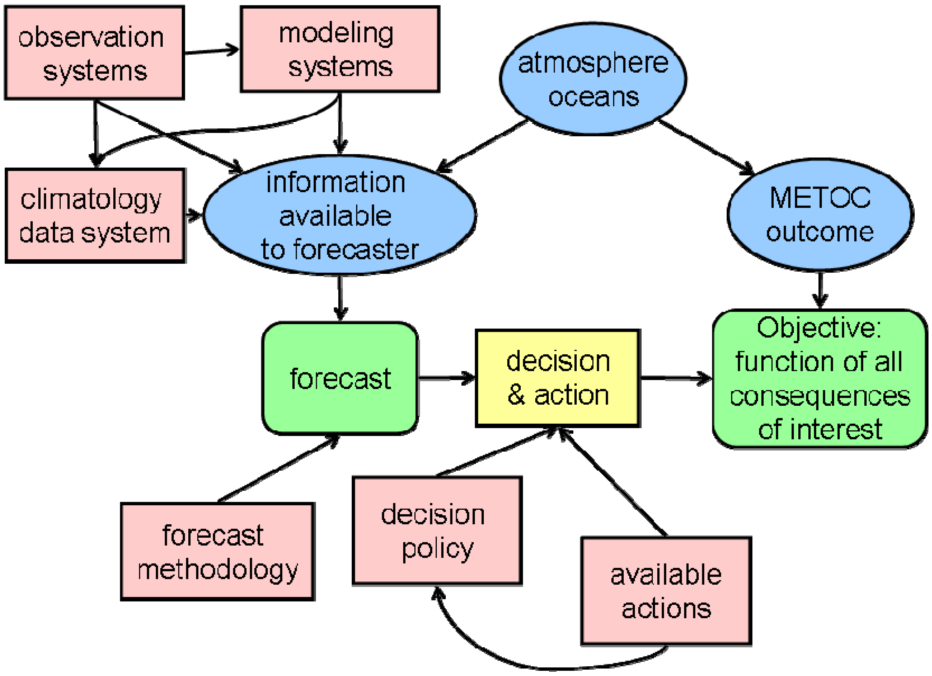


Figure 5: The system of interactions by which forecast information influences consequences.

There may be a special challenge for climatology as it may influence decisions more subtly, because clear METOC impacts on operations such as limits presented by operational thresholds will not be activated based on climatology. Decision and consequence models are expected to be less common for climatology-based decisions. These challenges should not discourage the METOC community from considering the interdependencies. The effects of changes in METOC systems on forecast value may need to be considered qualitatively and subjectively. Neglecting to consider these interactions in developing METOC systems will reduce METOC value relative to its potential, and perhaps even relative to its current value.

8 References

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Appendix A – The Missile Battle

The missile battle model is based on the basic salvo model by Hughes (1995), pitting Blue aircraft against Red vessels. Hughes assumes that two fleets of vessels, each fleet consisting of one type of vessel with one type of missile, engage in a missile exchange.

The missile exchange is divided into multiple salvos. In each salvo, a fraction of Red vessels are disabled and a fraction of Blue vessels are disabled, as determined by deterministic formulas based on the number of "well-aimed missiles" fired by each able vessel, the number of well-aimed missiles required to disable each type of vessel, and the number of missiles each vessel can defend against (per salvo).

Table A-1: Notation for salvo model, following Hughes (1995)

R_t	Number of able vessels in the Red force at the beginning of salvo t
B_t	Number of able vessels in the Blue force at the beginning of salvo t
$\rho(a_3)$	Number of well-aimed missiles fired by each Red vessel, a function of the Red's missile type selected (a_3) – when METOC conditions permit its use. When METOC conditions do not permit the use of the missile type selected, $\rho(a_3)$ =0.
$\beta(a_2)$	Number of well-aimed missiles fired by each Blue aircraft, a function of the Blue's missile type selected (a_2) – when METOC conditions permit its use. When METOC conditions do not permit the use of the missile type selected, $\beta(a_2)$ =0.
r_1	Number of hits by Blue's missiles required to disable one Red vessel (Red's staying power)
b_1	Number of hits by Red's missiles required to disable one Blue aircraft (Blue's staying power)
r_3	Number of well-aimed missiles destroyed by each Red vessel (Red's defensive capability)
b_3	Number of well-aimed missiles destroyed by each Blue aircraft (Blue's defensive capability)
ΔR_t	Number of Red vessels (potentially) destroyed by Blue's missiles during salvo t ; (unless $\Delta R_t > R_t$)
ΔB_t	Number of Blue aircraft (potentially) destroyed by Red's missiles during salvo t ; (unless $\Delta B_t > B_t$)

In addition to values for parameters described above, the following assumptions have been added to the Hughes model:

- Each missiles type is either usable or unusable, according to METOC conditions, as detailed in Table 3 in the body of the report. If missiles are usable, all fired missiles are well-aimed.
- Red has two vessel types – escorts and landing craft, and Blue does not distinguish between them in targeting. Parameters such as number of missiles fired per salvo per vessel are weighted averages based on the fraction of escort vessels among total Red vessels, and assuming no armament on the landing vessels.

- One salvo corresponds to one fighter sortie. Up to six sorties occur between the time Red vessels cross the neutral line and the time they land. (Using the parameter values given in Table A-2, either the Red or Blue fleet will be completely destroyed within six salvos.)

For each salvo,

$$R_{t+1} = \max\left\{0, R_t - \Delta R_t\right\},\ \Delta R_t = \frac{\beta\left(a_2\right) B_t - r_3 R_t}{r_1} \text{ and similarly}$$

$$B_{t+1} = \max\left\{0, B_t - \Delta B_t\right\},\ \ \Delta B_t = \frac{\rho\left(a_3\right) R_t - b_3 B_t}{b_1}.$$

The notation is defined in Table A-1 and parameter values used in the Halsey scenario example and the extended Halsey scenario (with climatology) are given in Table A-2.

Table A-2: Parameters of salvo model

R_0	275
B_0	48
$\rho\left(a_3\right)$	$= \begin{cases} 0.55 \text{ if } a_3 = \text{C (Type C missile used)} \\ 0.27 \text{ if } a_3 = \text{D (Type D missile used)} \end{cases}$
$\beta\left(a_2\right)$	$= \begin{cases} 10 \text{ if } a_2 = \text{A (Type A missile used)} \\ 6 \text{ if } a_2 = \text{B (Type B missile used)} \end{cases}$
r_1	4.27
b_1	2
r_3	0
b_3	1

Appendix B – Modeling and Solving Multi-stage Problems

The Decision Tree

Multi-stage problems are often represented using a decision tree, which makes it easy to understand precedence relationships and the analysis of the decisions. Events include decisions, receipt of information, and resolution of uncertainty. In a decision tree, events proceed chronologically from left to right. An example of a partial decision tree for the extended Halsey scenario is given in Figure B-1.

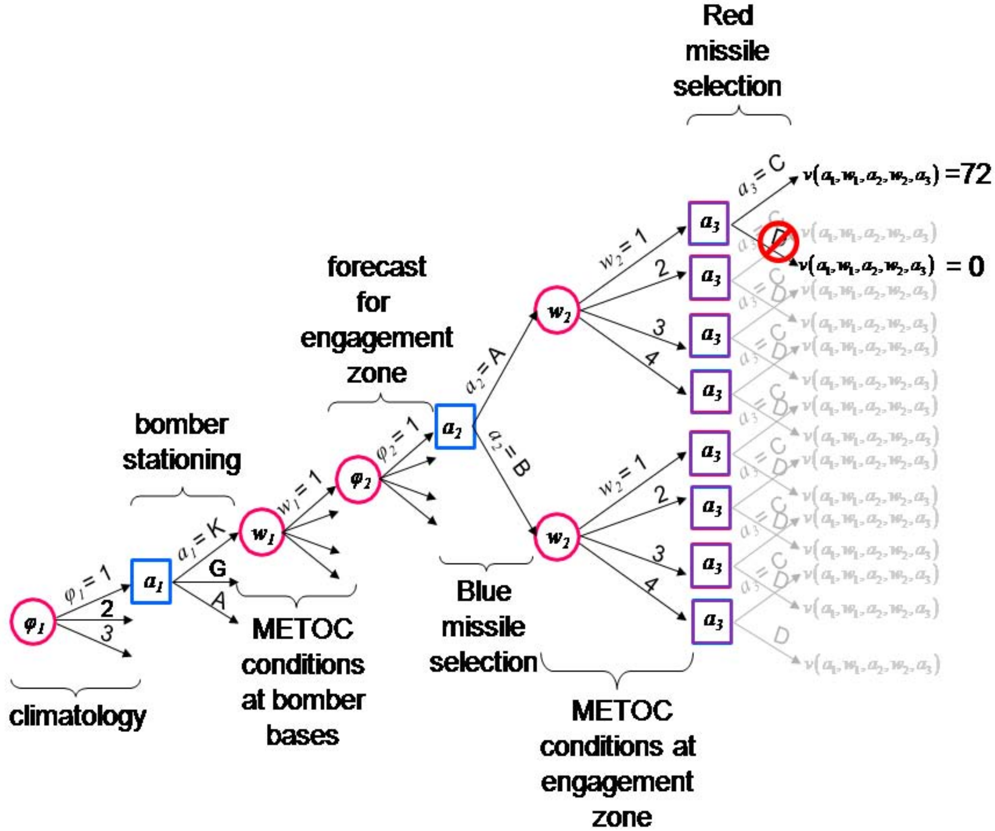

Figure B-1: Decision tree for expanded Halsey scenario

Nodes represent possible states of the system – for every possible scenario (defined by information sets received, choices of alternatives, and outcomes of early events) preceding each stage in the model, there will be a separate node. The unique arrow entering each node indicates which path (state of system) leads to the node. By convention, the node's shape and color indicate whether it is a decision (blue square), an uncertain variable (red circle). Uncertainty nodes are called chance nodes. In the case of decision nodes, arrows leaving the node indicate the alternatives available given that state of the system. In the case of chance nodes, arrows leaving the node indicate the possible outcomes of the uncertain event, usually with their probabilities indicated, as in Figure B-2.

The consequences of each possible path through the tree are shown at the end (far right) of the decision tree.

Analyzing the multi-stage problem

As discussed in Section 4.4, solutions are reached by backward induction: start with the last event(s) in the sequence, and work backwards. During the solution process, each node is assigned a value as follows:

- At each decision node, the commander chooses the branch that optimizes expected consequences (minimizes total cost) – this is the optimal decision for that node. Eliminate branches that are not optimal (prune the tree). Each decision node is assigned the value associated with the remaining branch. Eliminated branches should not figure in earlier decisions – assuming the commander will always make the right decisions, the eliminated branches will not be selected.
- Every chance node takes the expected value of the nodes to its right, where expectation is taken conditional on all information to that point.

This process is illustrated in Figure B-1 and Figure B-2. In Figure B-1, the top node at the far right is considered – this represents a decision node for Red (hence the mixed coloring of the square). This node represents the scenario in which climatology is $\varphi_1 = 1$, at the first decision opportunity, $a_1 =$ K (Kadena) is selected, $w_1 = 1$ occurs and becomes known to the commander, forecast $\varphi_2 = 1$ is issued, missile type $a_2 =$ A is selected, and finally (after Blue's missile selection decision) $w_2 = 1$ occurs and becomes known to the Red commander. Red has two choices – choosing missile Type C will result in 72 Red landing vessels surviving, while choosing Type D will result in zero Red landing vessels surviving. In this situation, we assume Red will rationally choose Type C missiles. The other alternative is eliminated and its branch is pruned from the tree (note that it does not appear in Figure B-2). The value 72 is assigned to the decision node.

In Figure B-2, all the right-most decision nodes have been analyzed. Next, two of the 288 chance nodes representing the outcome of METOC conditions in the engagement zone (w_2) are analyzed – by taking the expectation over the four possible outcomes. The node values are indicated in pink. Next, moving to the left, one of the decision nodes for Blue's missile-selection decision is analyzed – Blue will choose the branch with the lower value (minimizing the expected number of Red landing craft surviving to land), and the other branch is eliminated.

The process continues, with the tree rolled back and pruned at each decision node, until the first decision can be analyzed.

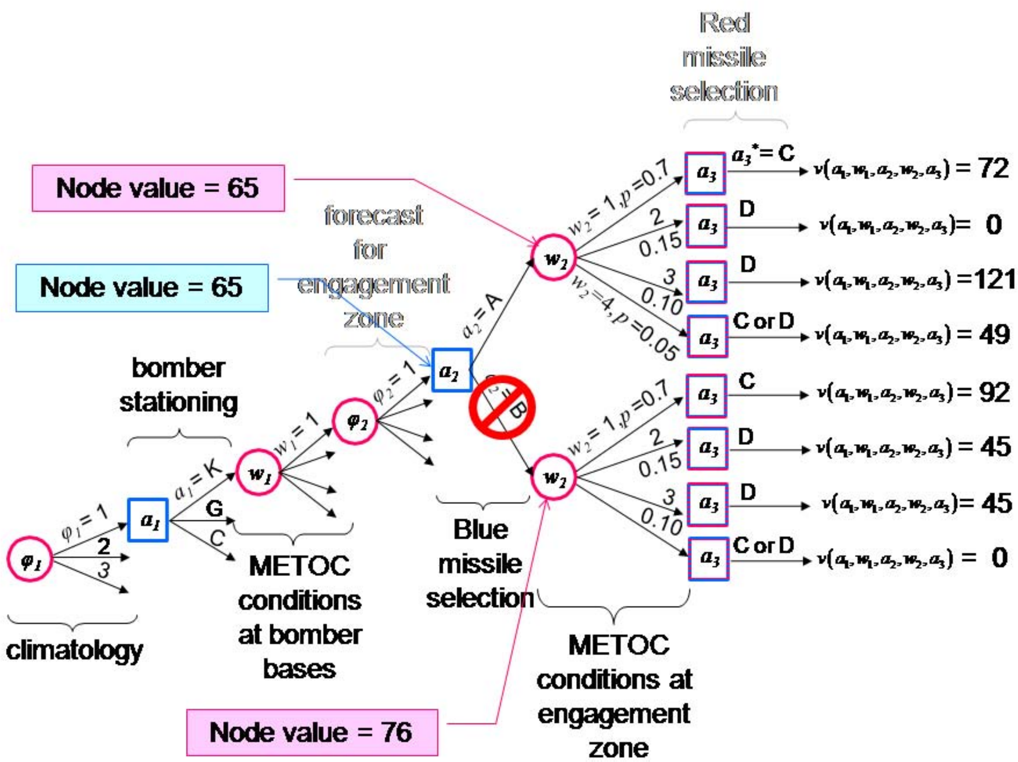

Figure B-2: Partially pruned decision tree for expanded Halsey scenario

Appendix C – Sea Mine Effectiveness

Like the missile exchange (described in Appendix A) sea mining is modeled very simply. We assume 12 mines per bomber aircraft, and 10 bombers, so each bomber can drop 120 mines per sortie. The transit time for Red is 18 hours, unless weather is very adverse ($w_2 = 4$). Therefore, if the bombers are stationed in Alaska ($a_1 = 3$), there will be zero sorties completed unless weather conditions are very severe ($w_2 = 4$).

Table C-1: Sea mine model notation

frontage	In feet, the length of the landing beach
	$= 3281 \cdot \frac{troops}{800}$, approximately 1 km per 800-person battalion
troops	Troop capacity of all Red landing craft = 17,580
r_M	Triggering radius of mine
M	Number of mines laid before Red vessels reach landing beach
n_{RVD}	Number of mines required to disable a Red vessel
λ	Average number of mines in fraction of minefield “swept” by a given vessel

	$= \dfrac{r_M}{frontage} \cdot M$

Further assumptions are:

- Mines are randomly (uniformly) distributed in minefield
- The number of mines is much greater than the number that are triggered (i.e. probability of a given ship encountering a mine does not decrease as mines are triggered by the ship or other ships)
- Radius for triggering is constant (assumed 30 feet)
- Number of mines triggered by a ship $\sim Poisson(\lambda)$.
- Number of mines that can be triggered by a vessel and have the vessel survive is $n_{RVD} - 1$, while if n_{RVD} are triggered, the vessel is disabled; n_{RVD} =2 assumed.
- Fraction of vessels disabled = expected probability that the number of mines triggered by a ship exceeds $n_{RVD} - 1$

$$p_M^{\psi} = \sum_{m=n_{RVD}}^{\infty} \underbrace{e^{-\lambda} \cdot \frac{\lambda^m}{m!}}_{\substack{\text{probability that} \\ m \text{ mines are} \\ \text{triggered}}} = 1 - \sum_{m=0}^{n_{RVD}-1} \underbrace{e^{-\lambda} \cdot \frac{\lambda^m}{m!}}_{\substack{\text{probability that} \\ m \text{ mines are} \\ \text{triggered}}}$$

Initial Distribution List

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

3. Ted Tsui
   Naval Research Laboratory
   7 Grace Hopper Ave, Monterey, California 93943-5502